The 2023 international workshop on CEPC

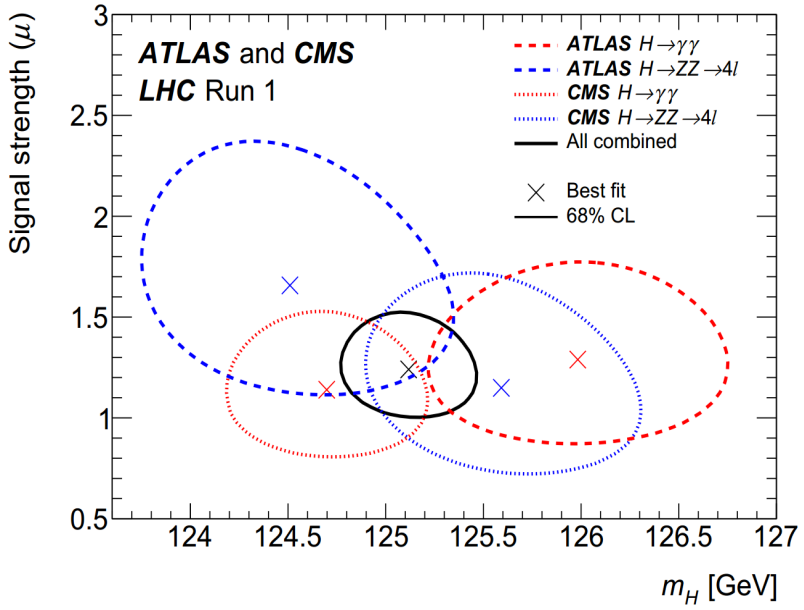
BSM Higgs physics at higher-orders

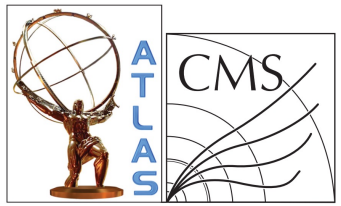
Wei Su

Outline

- Higgs Precision Measurements and 2HDM
- Study Results: exclusion ability
- Study Results: discovery potential
- Study Results: discrimination ability
- Study Results: Compatibility test
- Summary

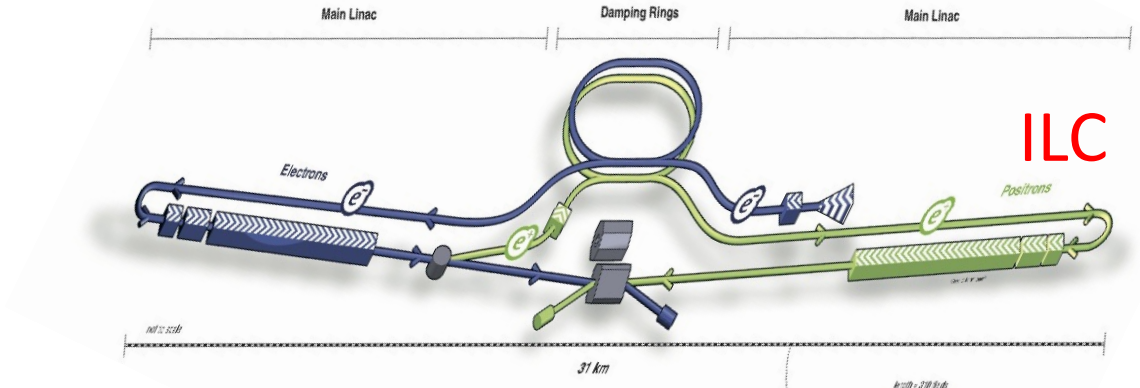
Higgs Precision Measurements



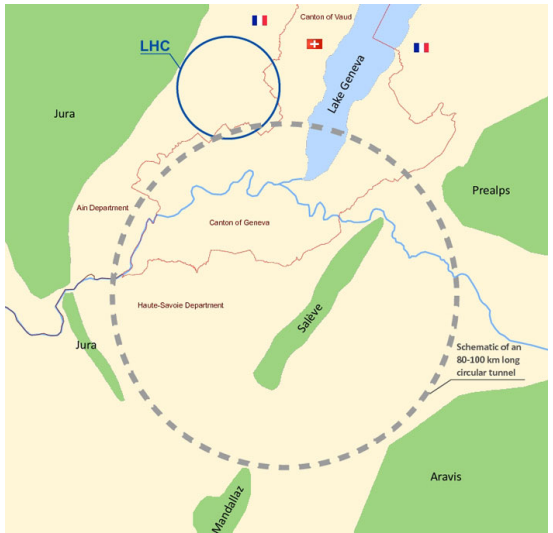


CMS-HIG-14-042
ATLAS-HIGG-2014-14

CEPC



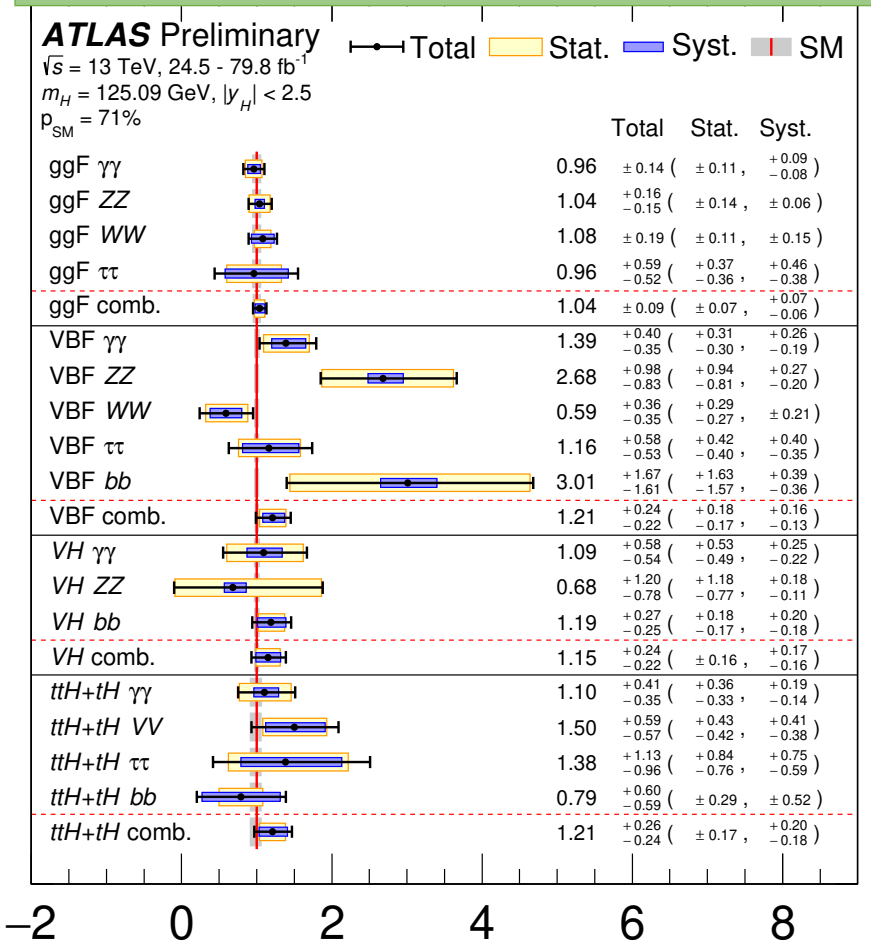
ILC



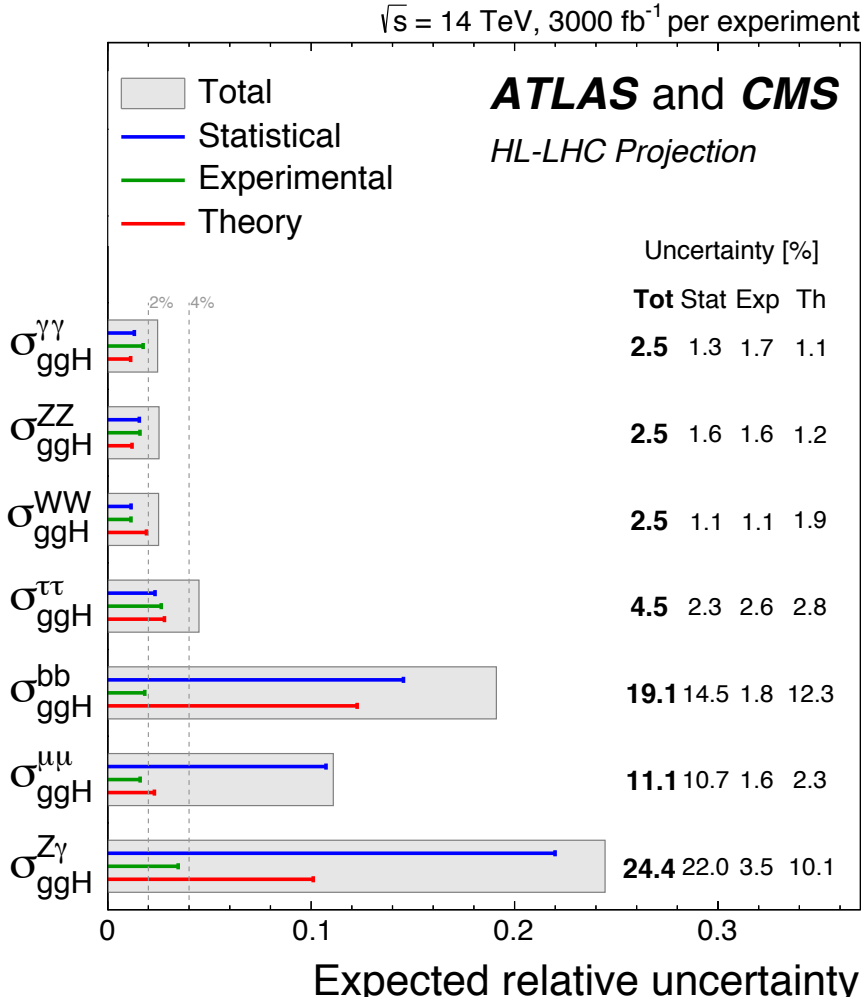
LHC
HL-LHC
FCC

Precision: Higgs couplings

LHC Run-II: ATLAS-CONF-2019-005



HL-LHC: 1902.00134



Precision: Higgs couplings

CEPC-CDR , FCC-ee, ILC Operating Scenarios

collider	CEPC	FCC-ee			ILC				
$\sqrt{s}$	240 GeV	240 GeV	365 GeV		250 GeV	350 GeV		500 GeV	
$\int \mathcal{L}dt$	5.6 ab^{-1}	5 ab^{-1}	1.5 ab^{-1}		2 ab^{-1}	200 fb^{-1}		4 ab^{-1}	
production	Zh	Zh	Zh	$\nu\bar{\nu}h$	Zh	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
$\Delta\sigma/\sigma$	0.5%	0.5%	0.9%	–	0.71%	2.0%	–	1.05	–
decay	$\Delta(\sigma \cdot BR)/(\sigma \cdot BR)$								
$h \to b\bar{b}$	0.27%	0.3%	0.5%	0.9%	0.46%	1.7%	2.0%	0.63%	0.23%
$h \to c\bar{c}$	3.3%	2.2%	6.5%	10%	2.9%	12.3%	21.2%	4.5%	2.2%
$h \to gg$	1.3%	1.9%	3.5%	4.5%	2.5%	9.4%	8.6%	3.8%	1.5%
$h \to WW^*$	1.0%	1.2%	2.6%	3.0%	1.6%	6.3%	6.4%	1.9%	0.85%
$h \to \tau^+\tau^-$	0.8%	0.9%	1.8%	8.0%	1.1%	4.5%	17.9%	1.5%	2.5%
$h \to ZZ^*$	5.1%	4.4%	12%	10%	6.4%	28.0%	22.4%	8.8%	3.0%
$h \to \gamma\gamma$	6.8%	9.0%	18%	22%	12.0%	43.6%	50.3%	12.0%	6.8%
$h \to \mu^+\mu^-$	17%	19%	40%	–	25.5%	97.3%	178.9%	30.0%	25.0%
$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	3.1%	–	–	3.7%	–	–	–	–

Precision: Higgs couplings

CEPC-CDR , FCC-ee, ILC Operating Scenarios

collider	CEPC	FCC-ee			ILC				
$\sqrt{s}$	240 GeV	240 GeV	365 GeV		250 GeV	350 GeV		500 GeV	
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production	Zh	Zh	Zh	$\nu\bar{\nu}h$	Zh	Zh	$\nu\bar{\nu}h$	Zh	$\nu\bar{\nu}h$
$\Delta\sigma/\sigma$	0.5%	0.5%	0.9%	–	0.71%	2.0%	–	1.05	–
$h \to b\bar{b}$	0.27%	0.3%	0.5%	0.9%	0.46%	1.7%	2.0%	0.63%	0.25%
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$h \to gg$	1.3%	1.9%	3.5%	4.5%	2.5%	9.4%	8.6%	3.8%	1.5%
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$(\nu\bar{\nu})h \to b\bar{b}$	2.8%	3.1%	–	–	3.7%	–	–	–	–

Exclusion, discovery, discrimination, Compatibility test

2HDM: Brief Introduction

- Two Higgs Doublet Model

$$\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + iG_i)/\sqrt{2} \end{pmatrix}$$

$$v_u^2 + v_d^2 = v^2 = (246\text{GeV})^2$$
$$\tan\beta = v_u/v_d$$

$$\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \quad \begin{aligned} A &= -G_1 \sin\beta + G_2 \cos\beta \\ H^\pm &= -\phi_1^\pm \sin\beta + \phi_2^\pm \cos\beta \end{aligned}$$

	Φ_1	Φ_2
Type I	u,d,l	
Type II	u	d,l
lepton-specific	u,d	l
flipped	u,l	d

- Parameters (CP-conserving, Flavor Limit, Z_2 Symmetry)

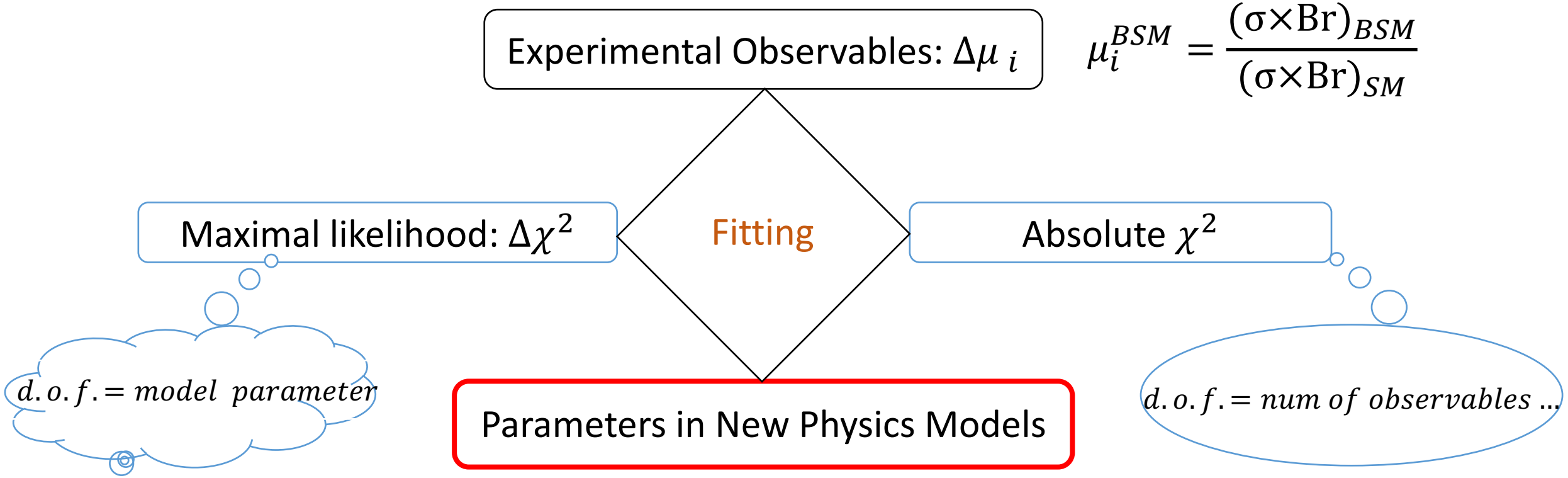
$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ → $v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$

Soft Z_2 symmetry breaking: m_{12}^2

246 GeV

125. GeV

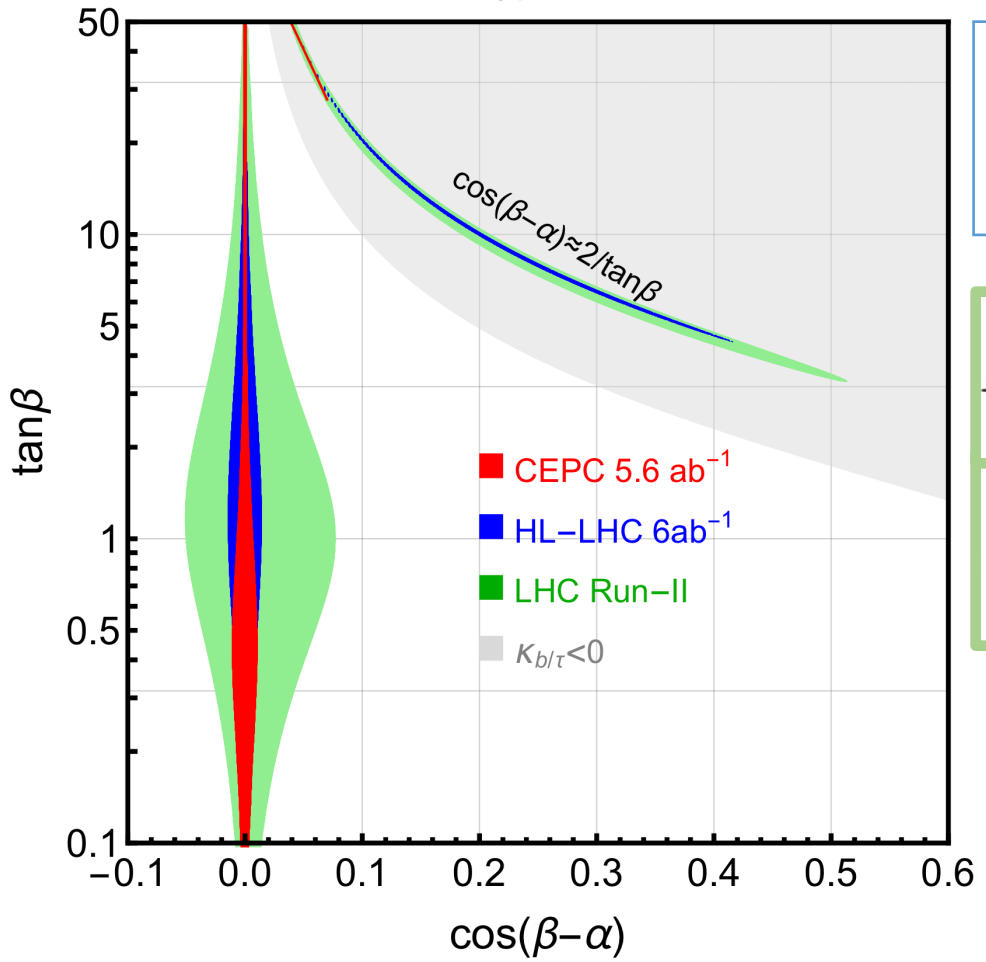
Exclusion ability : Study strategies



Exclusion: Tree Leve

Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

2HDM Type-II



Alignment limit :

$\cos(\beta-\alpha)=0$

$g(2HDM)=g(SM)$

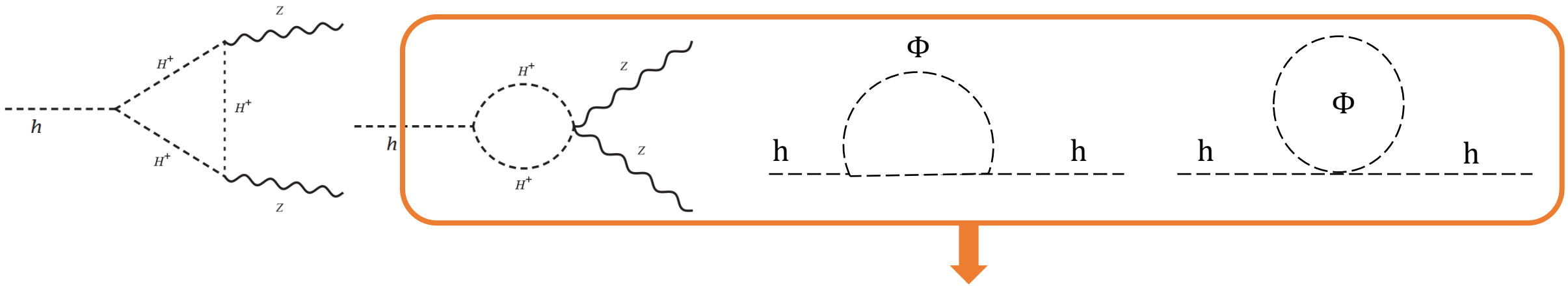
1910.06269

WS

$$-\frac{\sin\beta}{\cos\alpha}-1=-\frac{1}{2}\cos^2(\beta-\alpha)-\cos(\beta-\alpha)\times\tan\beta$$

$$\frac{\cos\alpha}{\sin\beta}-1=-\frac{1}{2}\cos^2(\beta-\alpha)+\frac{\cos(\beta-\alpha)}{\tan\beta}$$

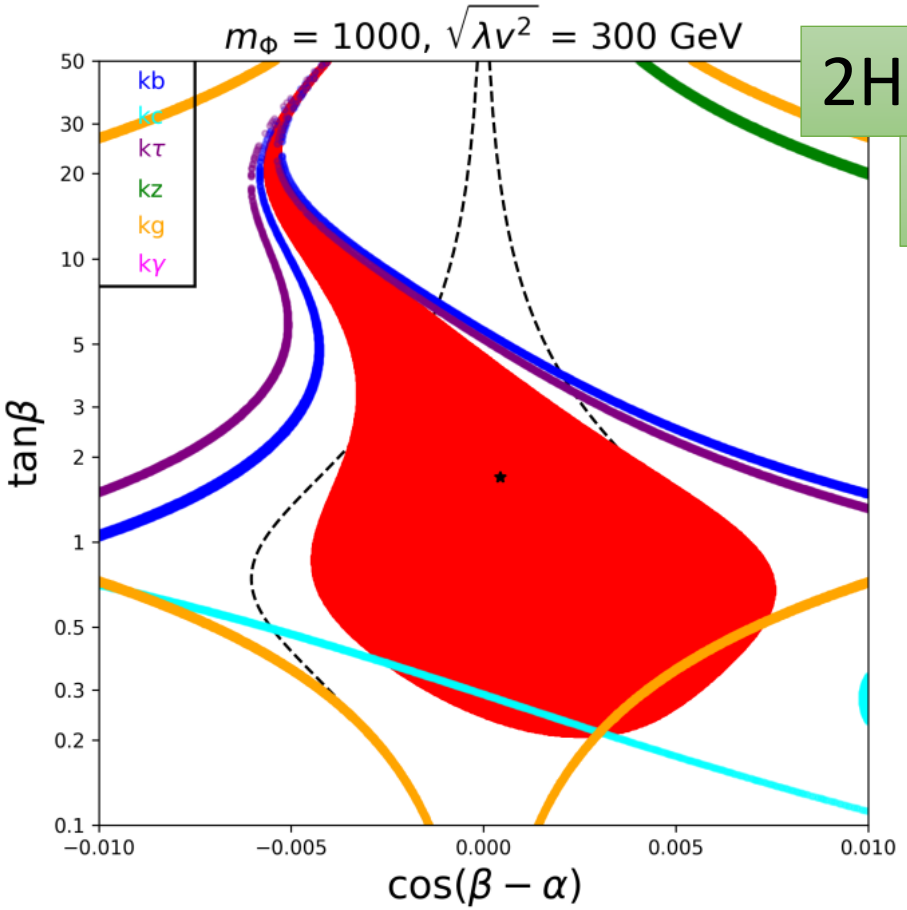
2HDM: One-Loop Level



Main contribution

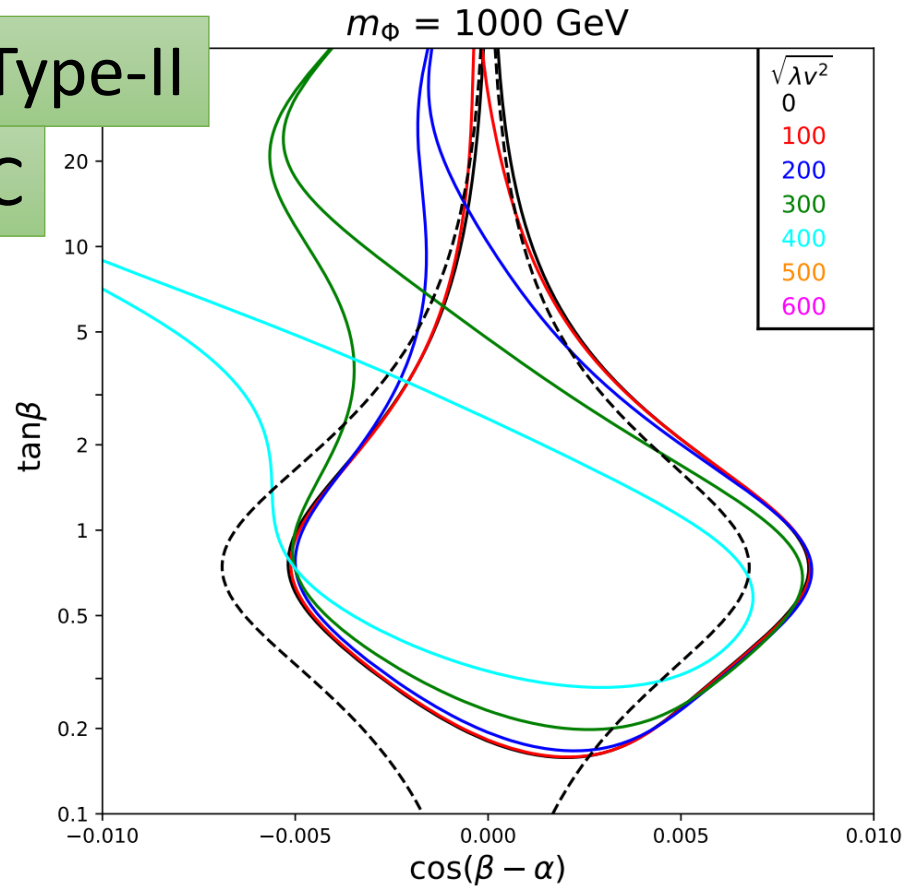
Parameter : $\cos(\beta-\alpha), \tan\beta, m_H, m_A, m_{H^\pm}, m_{12}^2$

Exclusion : Loop Level



2HDM Type-II

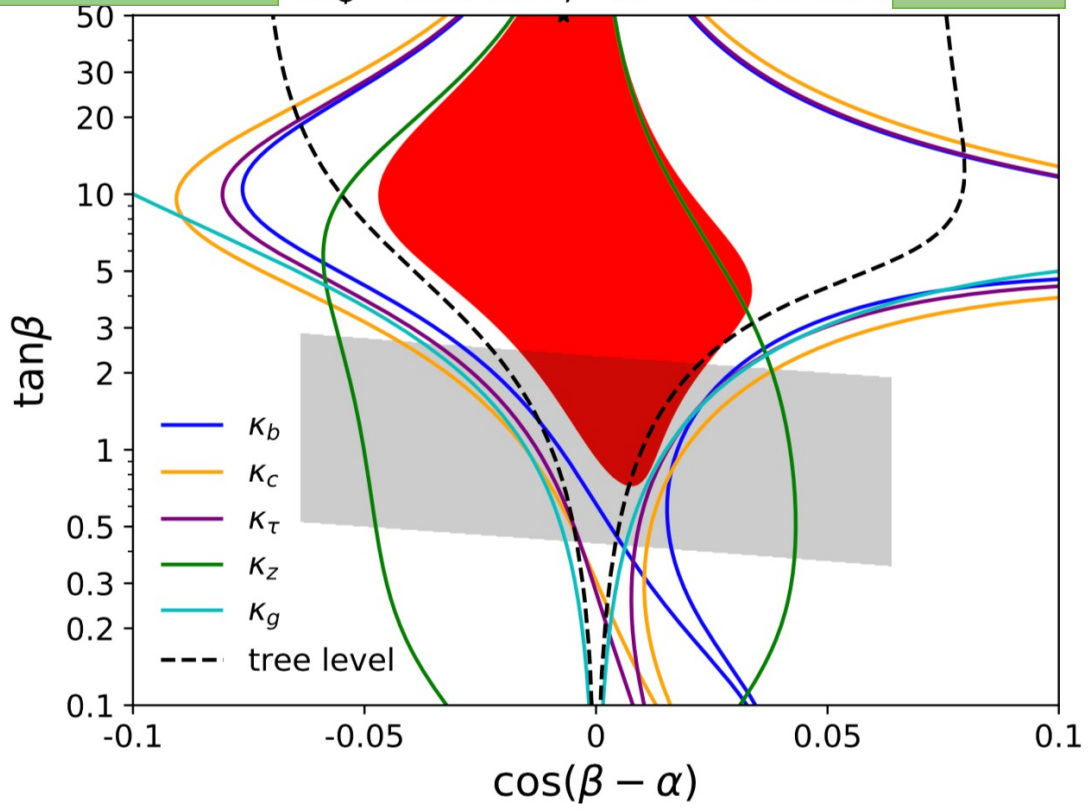
CEPC



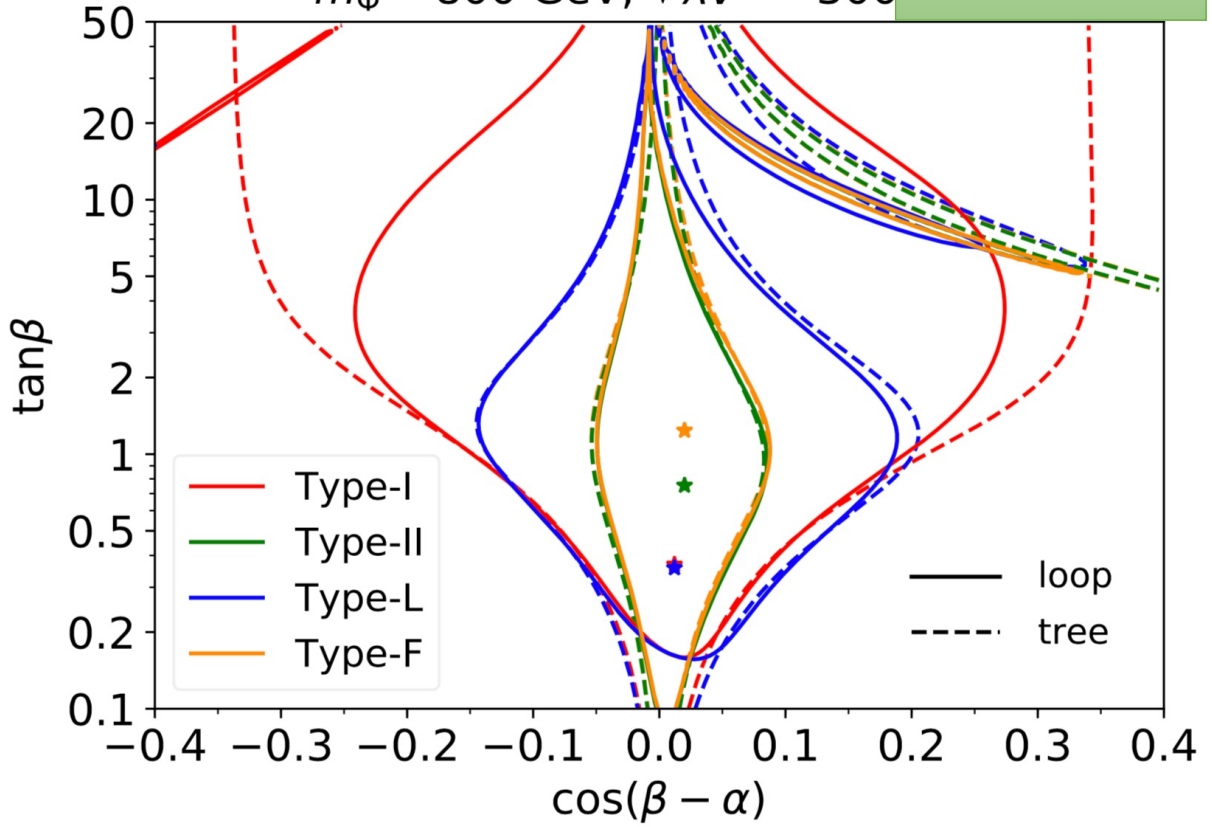
Exclusion : Loop Level

2HDM Type-I

CEPC



LHC Run-II



Study Results: discovery potential

- method

$$\chi^2 = \sum_i \frac{(\mu_i^{\text{hyp}} - \mu_i^{\text{obs}})^2}{\sigma_{\mu_i}^2}$$

null hypothesis H0 : SM

To claim the discovery of BSM at 5σ significance : p=5.7*10^(-7)

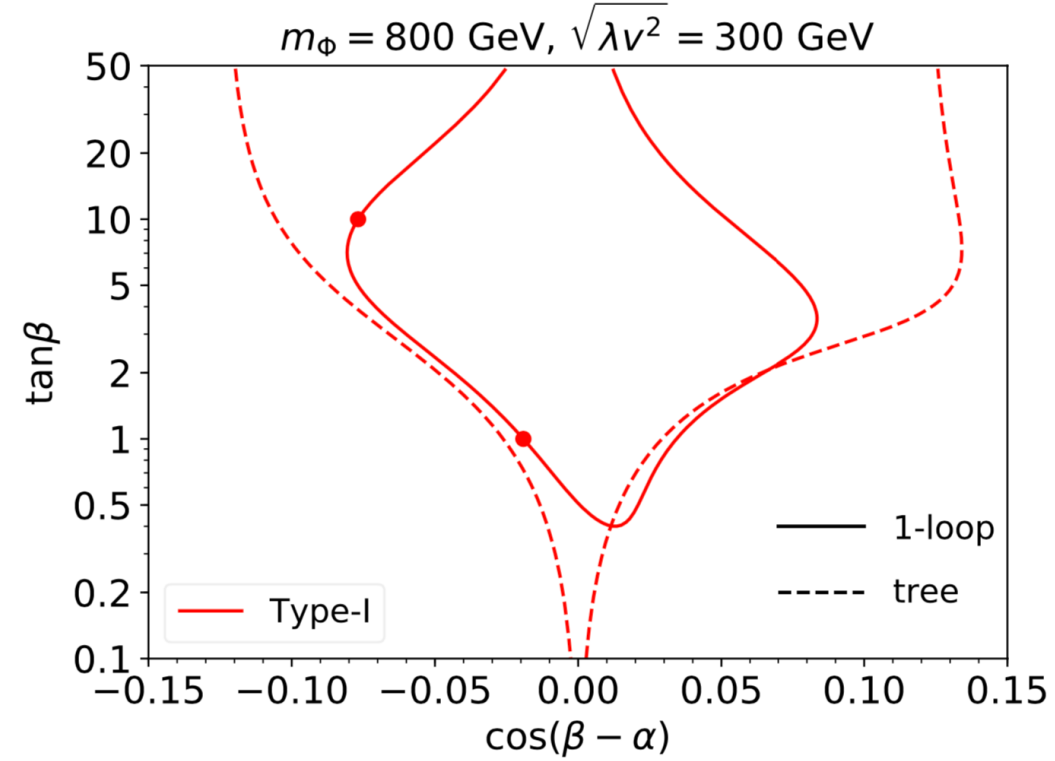
$$\chi^{\text{SM}} > 48.2$$

$$\mu^{\text{hyp}} = \mu^{\text{SM}} = 1$$

degrees of freedom : signal strength modifiers (SSM),
or μ parameter : 10 for CEPC

Study Results: discovery potential

Choose one point of BSM as the observed, to see if SM is rejected.

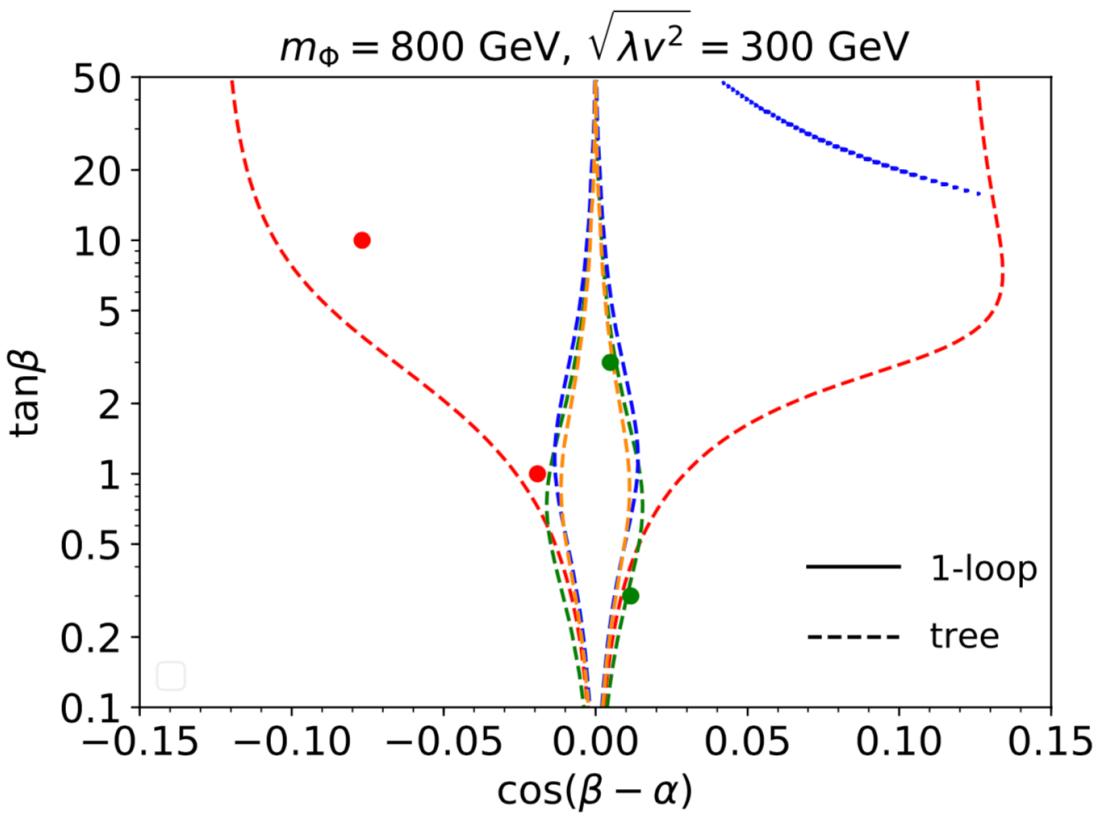


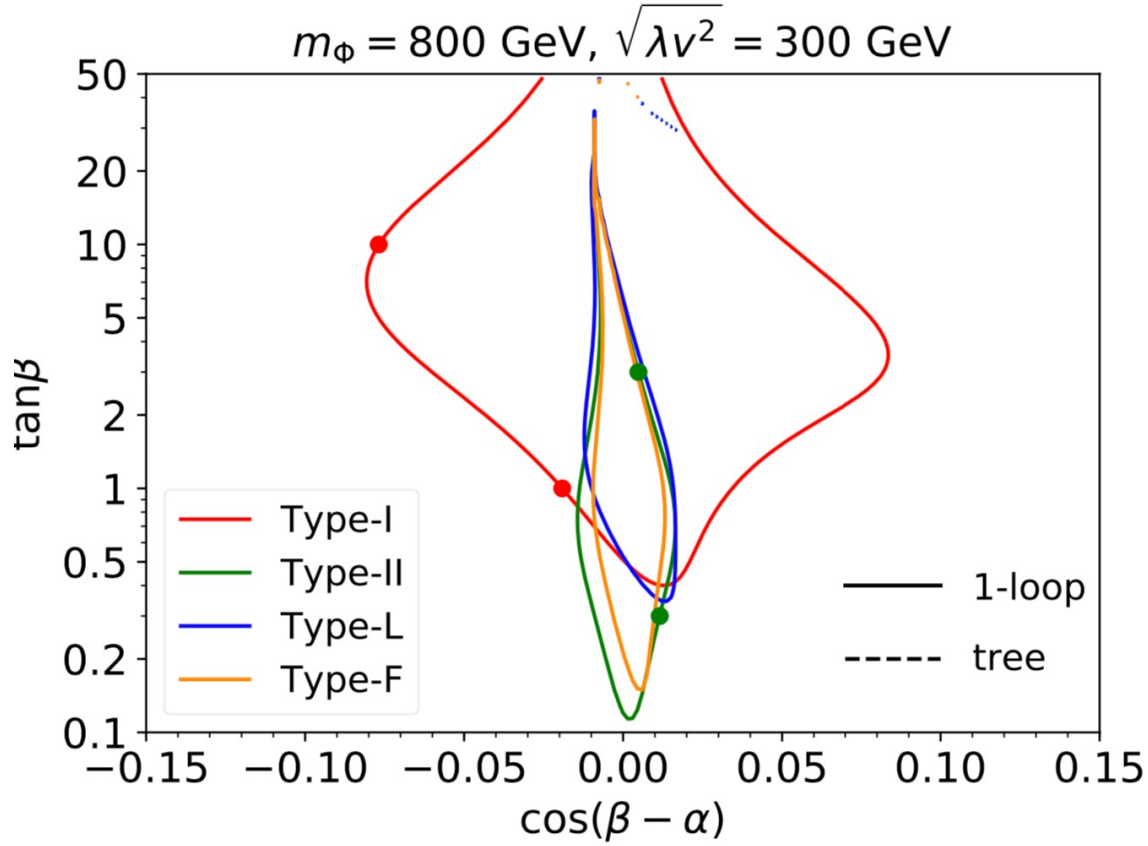
If the future observable is same to Type-I,
The center region can not claim a discovery
The two sides region can claim

$$\cos(\beta-\alpha) \lesssim -0.1$$

$$\cos(\beta-\alpha) \gtrsim 0.08$$

Study Results: discovery potential





Type-II, L, F: $|\cos(\beta - \alpha)| \gtrsim 0.02$ for $\tan\beta \sim 1$

Study Results: discrimination ability

- method

performing the χ^2 statistic

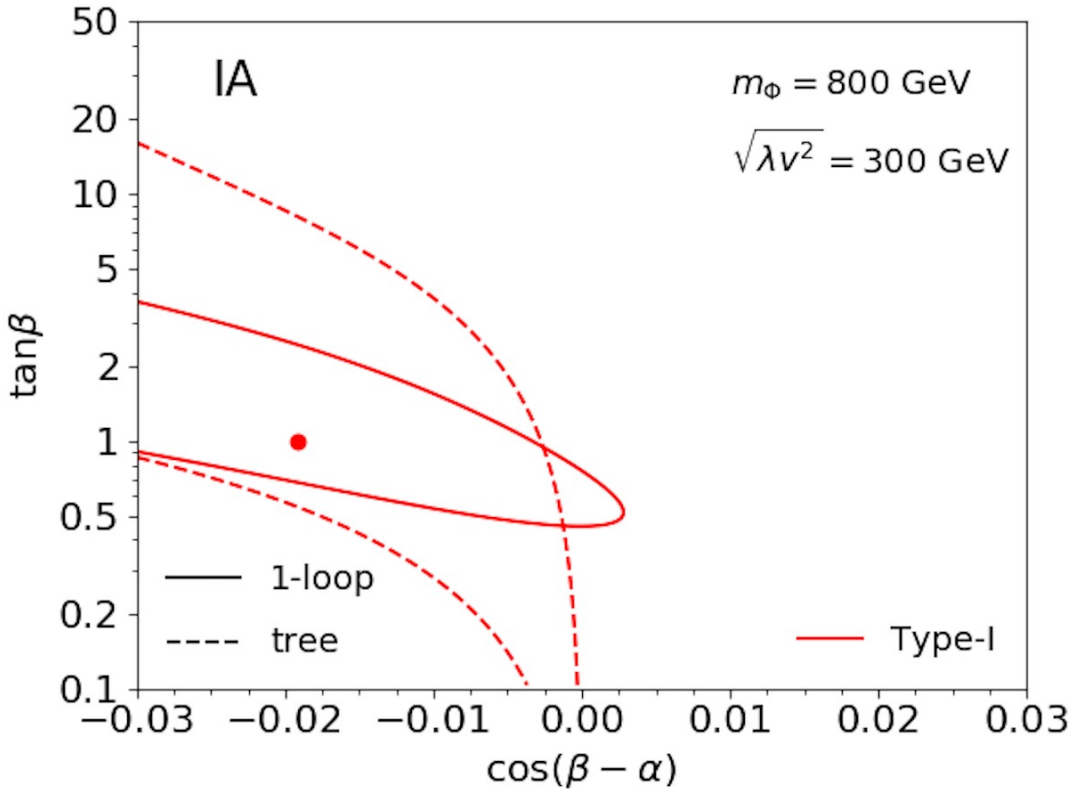
d.o.f. = # SSMs (μ) hypothesized model (Null model): One physical point

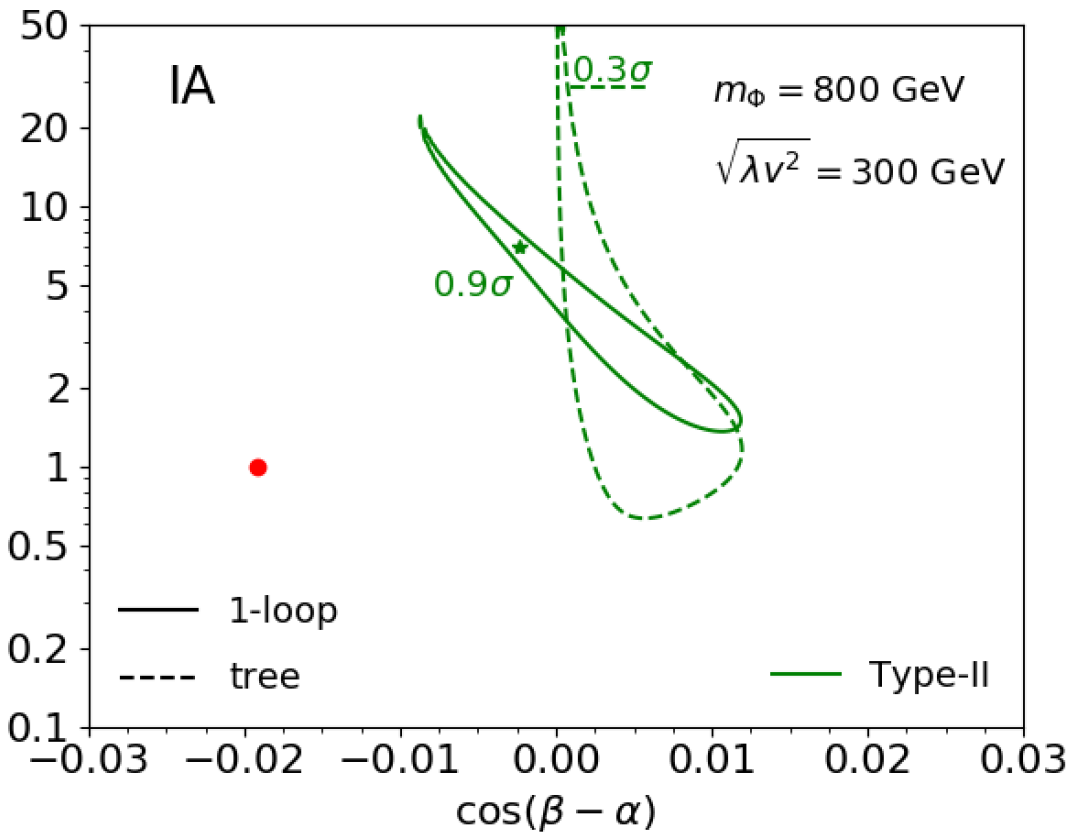
d.o.f.	1	2	3	4	5	6	7	8	9	10
$\chi^2(p = 0.05)$	3.84	5.99	7.81	9.49	11.1	12.6	14.1	15.5	16.9	18.3

BMs:

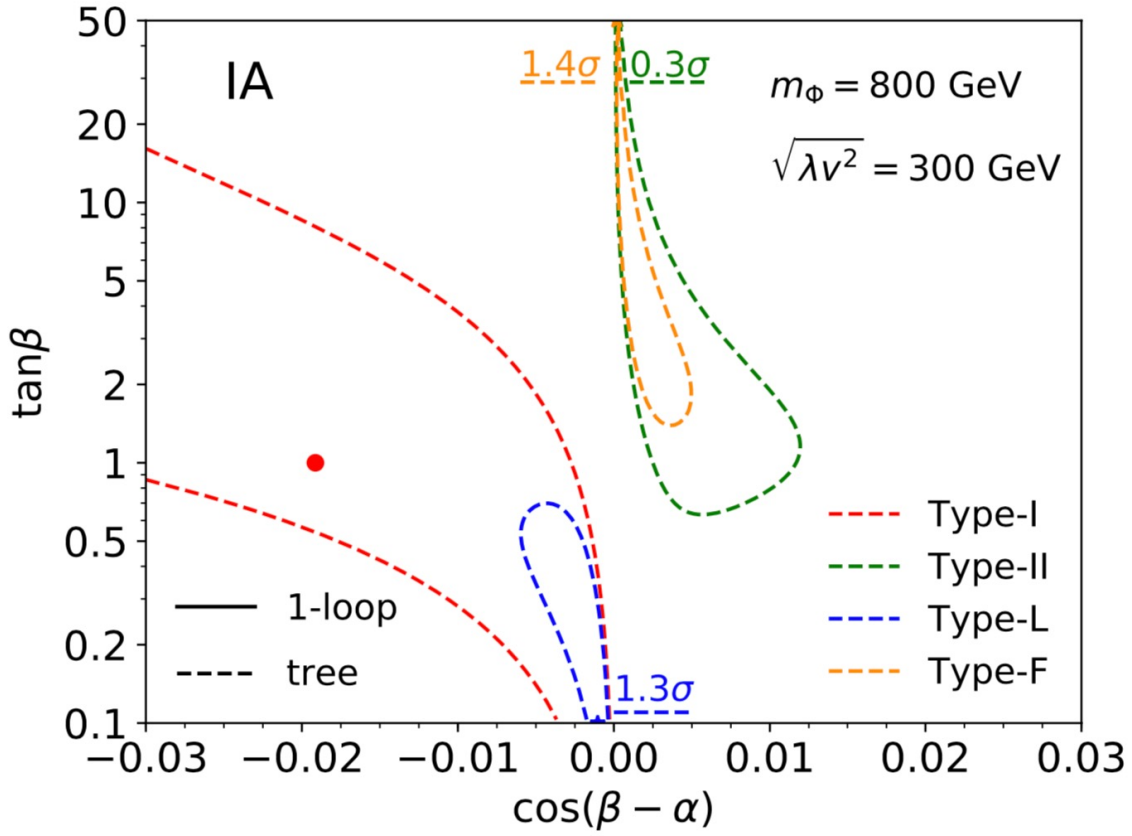
$(\cos(\beta-\alpha), \tan\beta)$	Small $\tan\beta$	Large $\tan\beta$
Type-I	**IA:** $(-0.019, 1.0)$	**IB:** $(-0.077, 10)$
Type-II	**IIA:** $(0.012, 0.3)$	**IIB:** $(0.005, 3.0)$

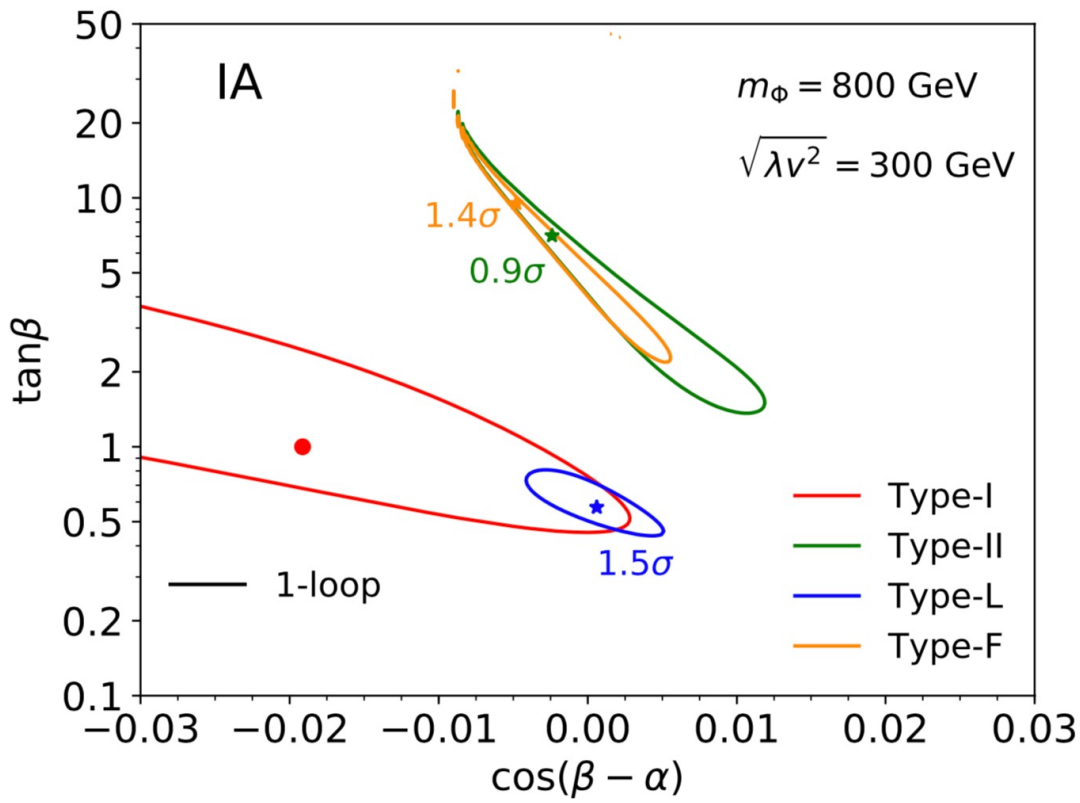
Study Results: discrimination ability





Study Results: discrimination ability





Study Results: compatibility test

- compatibility test method

Test Type-I with Type-II:

observable : one point of type-II (accepted model),

test type-I by performing the χ^2 statistic

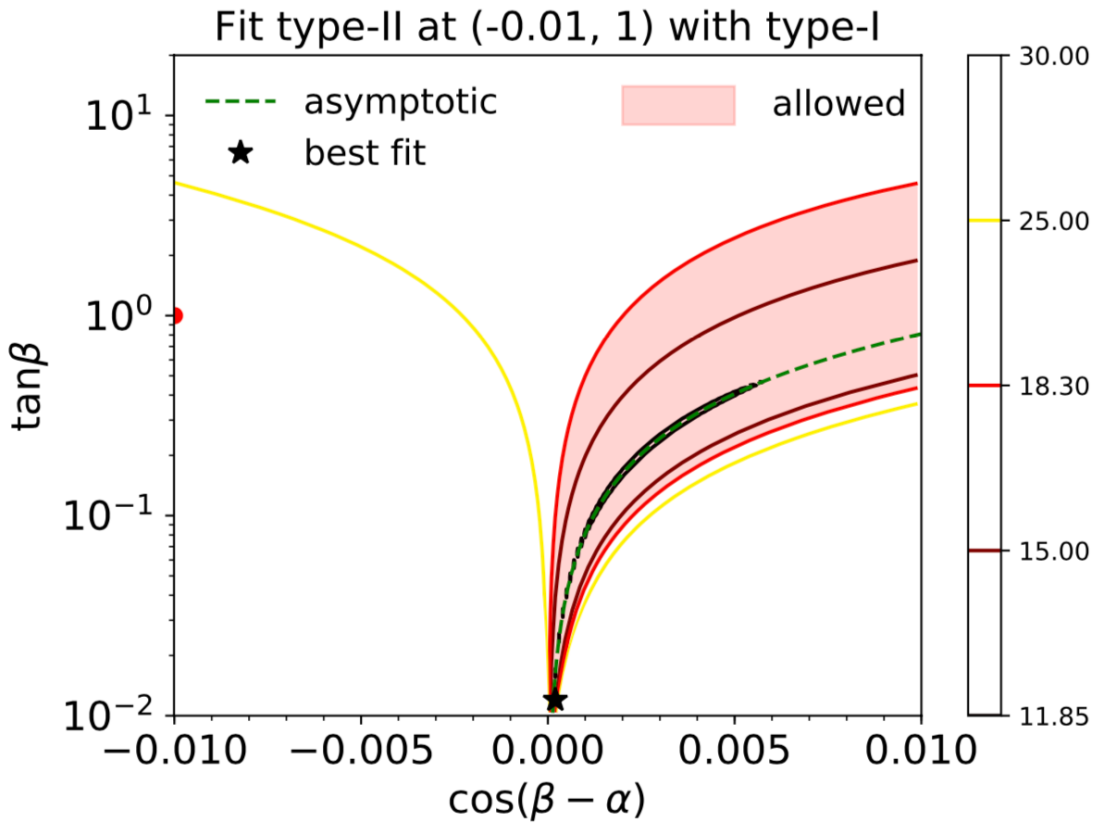
d.o.f. = # SSMs (μ)

hypothesized model (Null model): Type-II, instead of SM

d.o.f.	1	2	3	4	5	6	7	8	9	10
$\chi^2(p = 0.05)$	3.84	5.99	7.81	9.49	11.1	12.6	14.1	15.5	16.9	18.3

Study Results: compatibility test

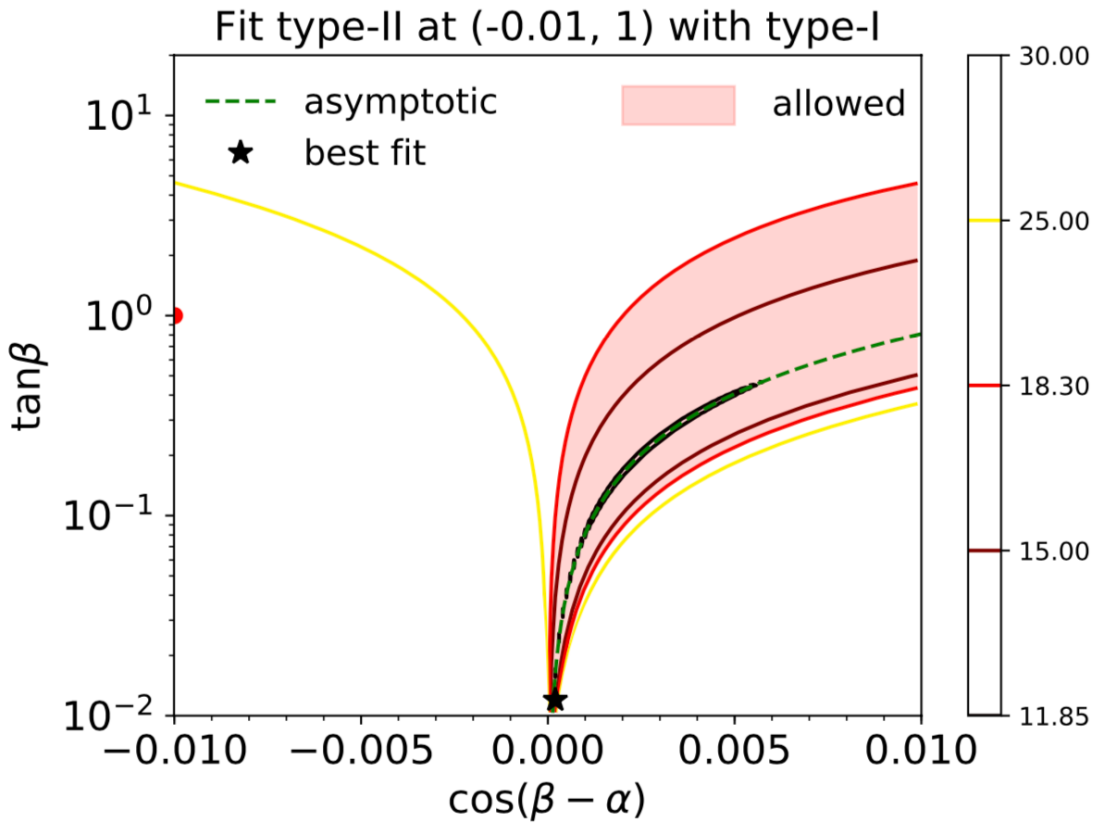
- Type-II $(\cos(\beta-\alpha), \tan\beta) = (-0.01, 1)$

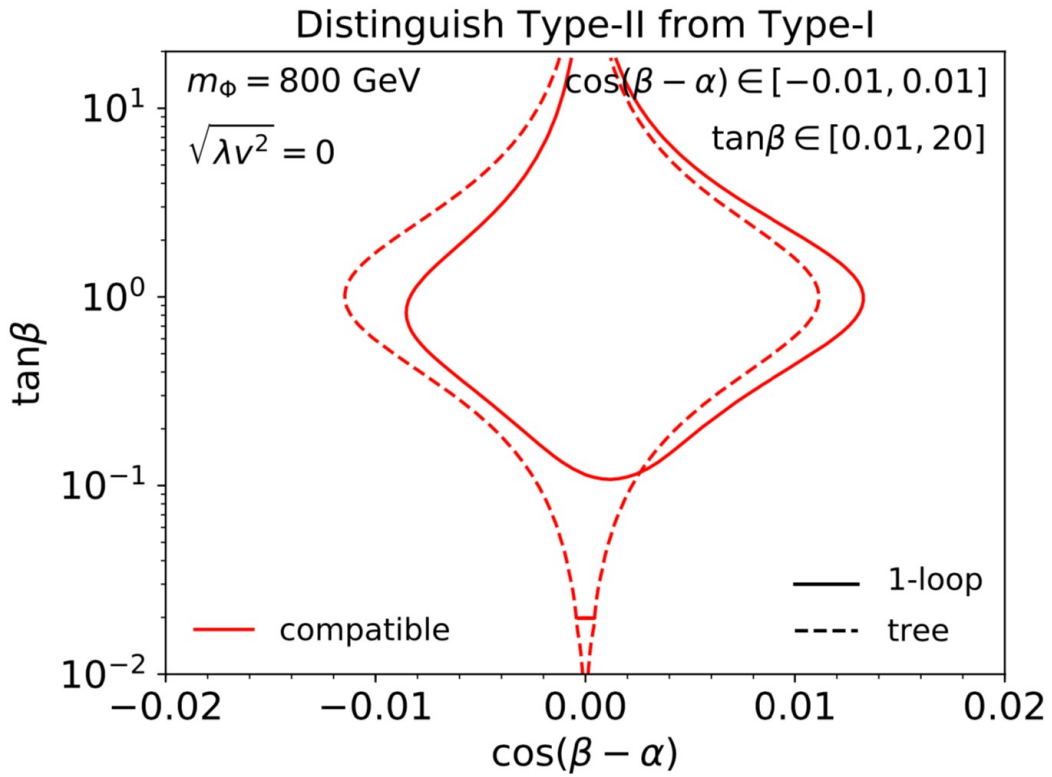


If there is points of Type-I is allowed, then BM of Type-II is compatible under CEPC precision

Study Results: compatibility test

- Type-II $(\cos(\beta-\alpha), \tan\beta) = (-0.01, 1)$





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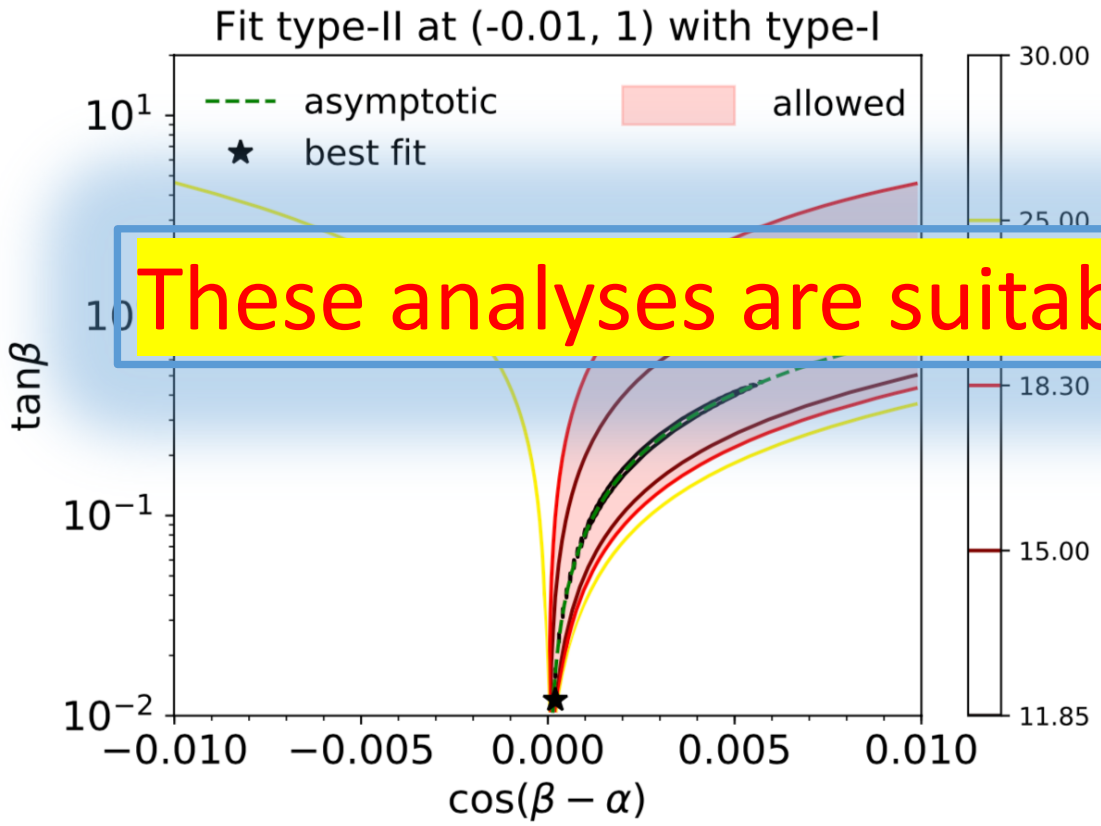
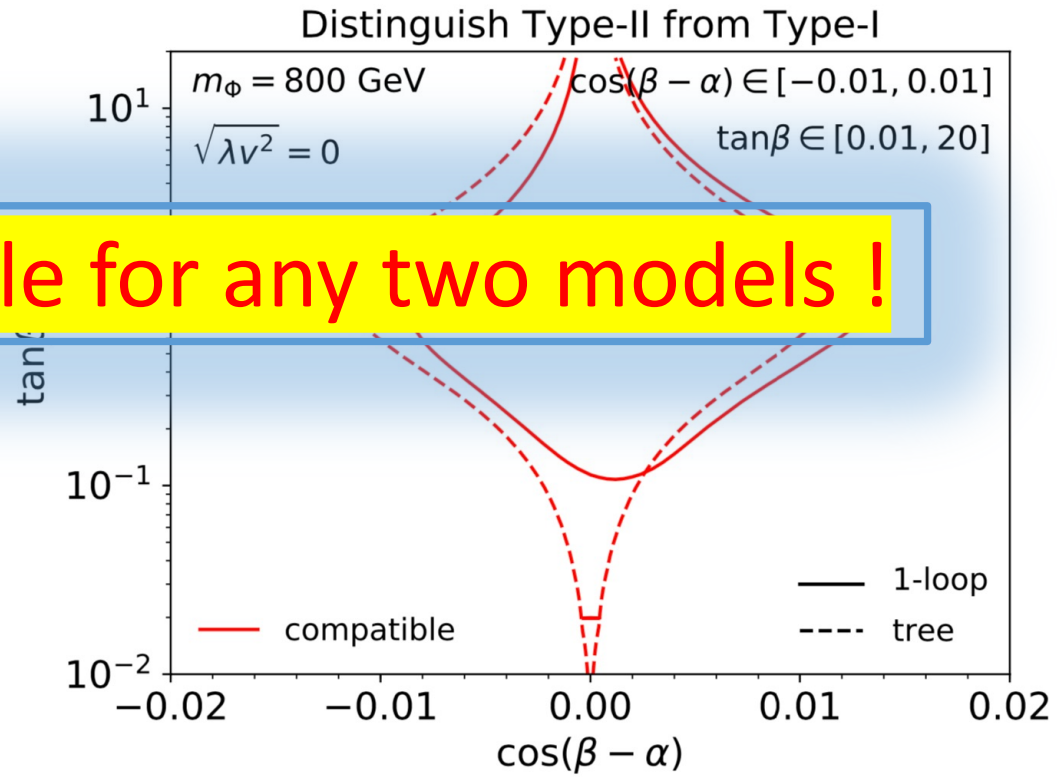
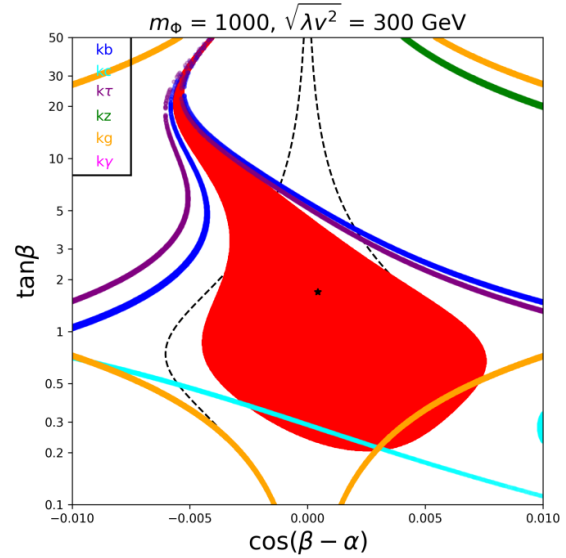


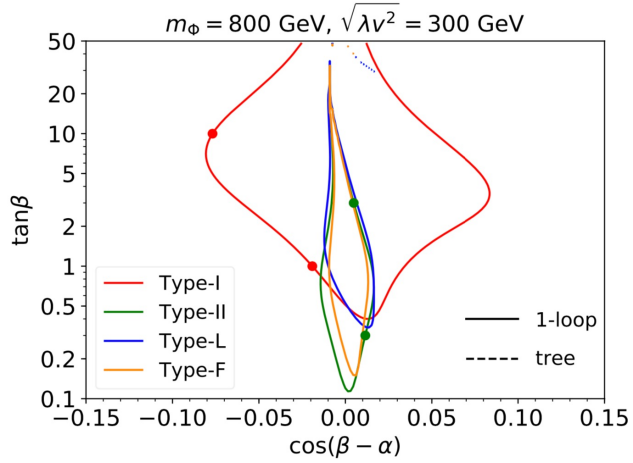


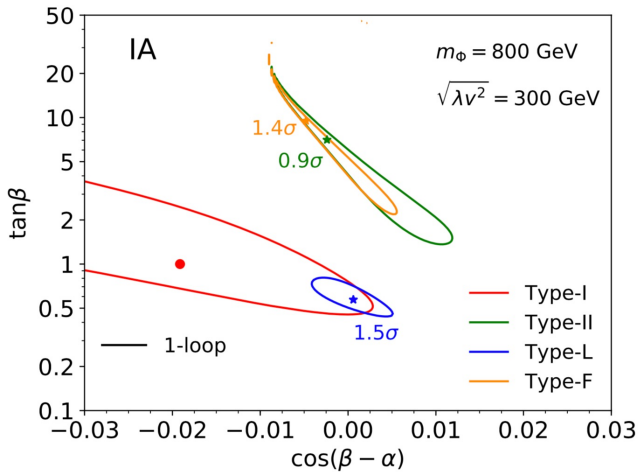
These analyses are suitable for any two models !

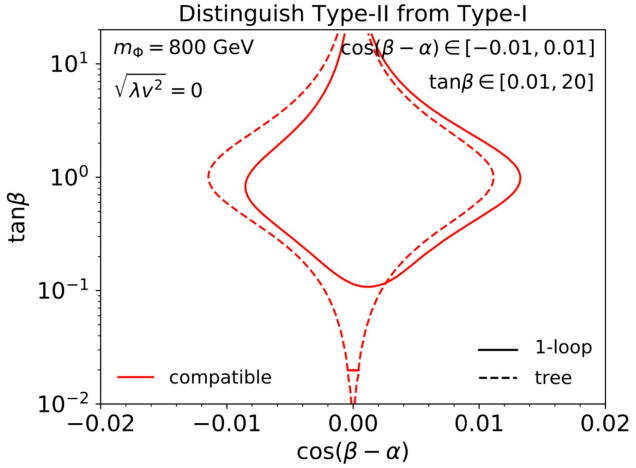
Summary: Higgs precision measurements

- Exclusion :Maximal likelihood vs. absolute χ^2 study
- Discovery potential: test null model SM
- Discrimination ability: a deviation observed
- Compatibility test: different BSMs









Thanks !

Backup

2HDM: Brief Introduction

- Two Higgs Doublet Model

$$
\begin{aligned}
V(\Phi_1,\Phi_2) = \; & m_{11}^2\Phi_1^\dagger\Phi_1 + m_{22}^2\Phi_2^\dagger\Phi_2 - m_{12}^2(\Phi_1^\dagger\Phi_2 + h.c.) + \frac{\lambda_1}{2}(\Phi_1^\dagger\Phi_1)^2 + \frac{\lambda_2}{2}(\Phi_2^\dagger\Phi_2)^2 \\
& + \lambda_3(\Phi_1^\dagger\Phi_1)(\Phi_2^\dagger\Phi_2) + \lambda_4(\Phi_1^\dagger\Phi_2)(\Phi_2^\dagger\Phi_1) + \frac{1}{2}\left[\lambda_5(\Phi_1^\dagger\Phi_2)^2 + h.c.\right] \\
& + \frac{1}{2}(\Phi_1^\dagger\Phi_2 + h.c.)(\lambda_6\Phi_1^\dagger\Phi_1 + \lambda_7\Phi_1^\dagger\Phi_1)
\end{aligned}
$$

$$
\Phi_i = \begin{pmatrix} \phi_i^+ \\ (v_i + \phi_i^0 + iG_i)/\sqrt{2} \end{pmatrix}
$$

$$
v_u^2 + v_d^2 = v^2 = (246\mathrm{GeV})^2
$$

$$
\tan\beta = v_u/v_d
$$

$$
\begin{pmatrix} H^0 \\ h^0 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}, \qquad \begin{aligned} A &= -G_1\sin\beta + G_2\cos\beta \\ H^\pm &= -\phi_1^\pm\sin\beta + \phi_2^\pm\cos\beta \end{aligned}
$$

2HDM: Brief Introduction

	Φ_1	Φ_2
Type I	u,d,l	
Type II	u	d,l
lepton-specific	u,d	l
flipped	u,l	d

$$\kappa_i = g_{hii}^{BSM} / g_{hii}^{SM}$$

Model	κ_V	κ_u	κ_d	κ_ℓ
2HDM-I	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
2HDM-II	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
2HDM-L	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
2HDM-F	$\sin(\beta-\alpha)$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$

- Parameters (CP-conserving, Flavor Limit, Z_2 Symmetry)

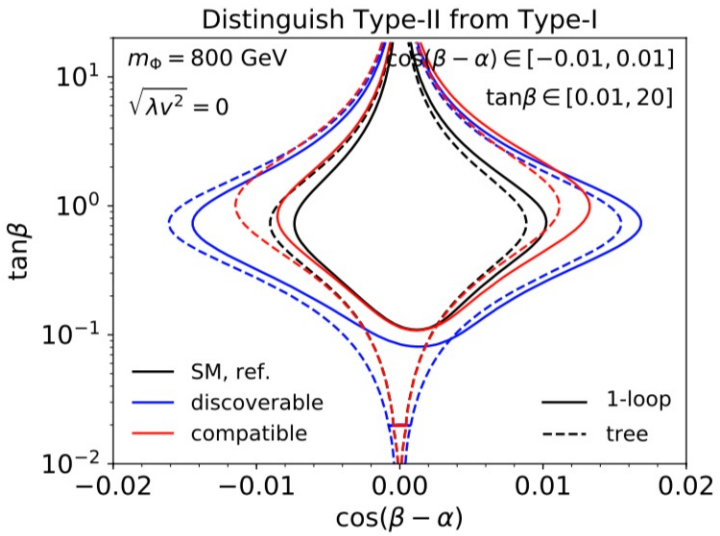
$m_{11}^2, m_{22}^2, \lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5$ → $v, \tan\beta, \alpha, m_h, m_H, m_A, m_{H^\pm}$

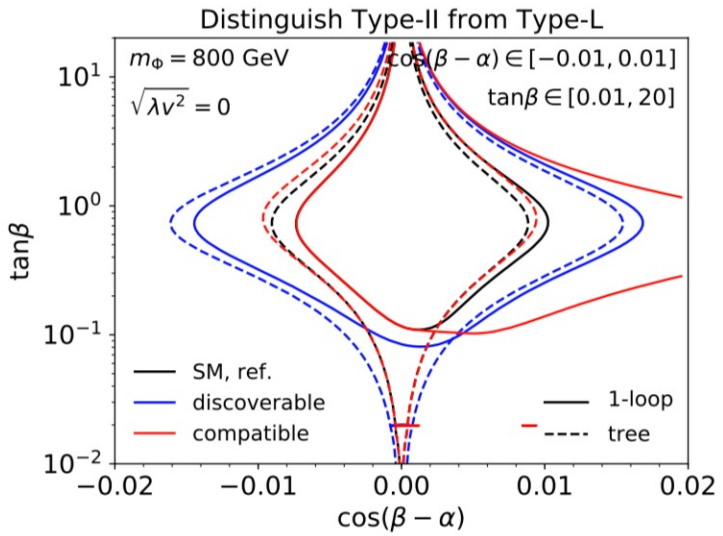
Soft Z_2 symmetry breaking: m_{12}^2

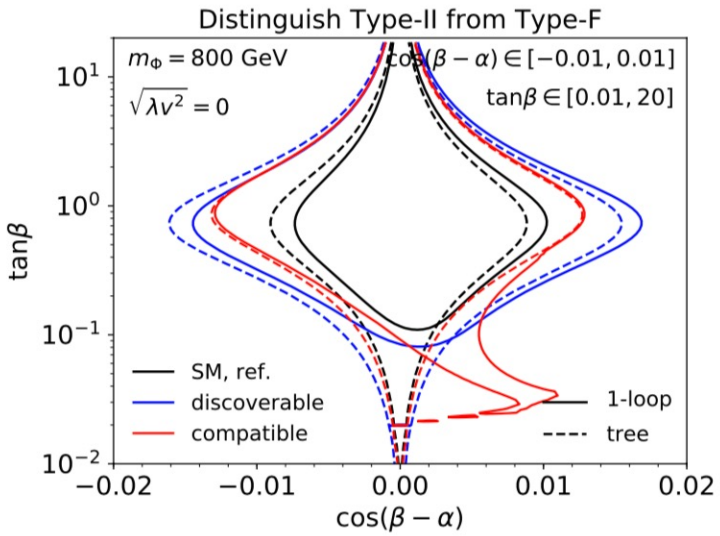
246 GeV

125. GeV

Study Results: compatibility test

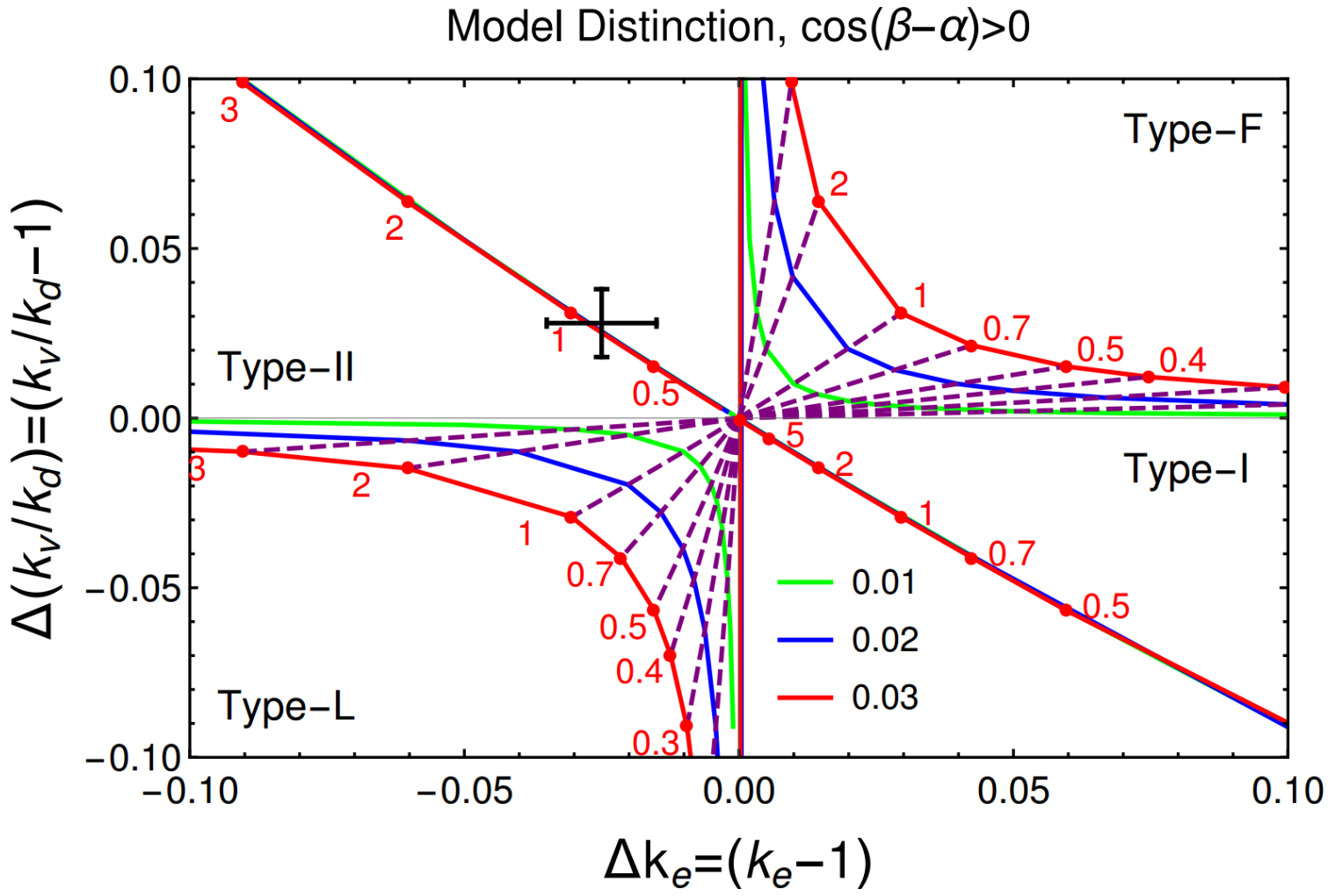






We can do the similar research between any two models

2HDM: Tree Level Model Distinction



Varying tan β

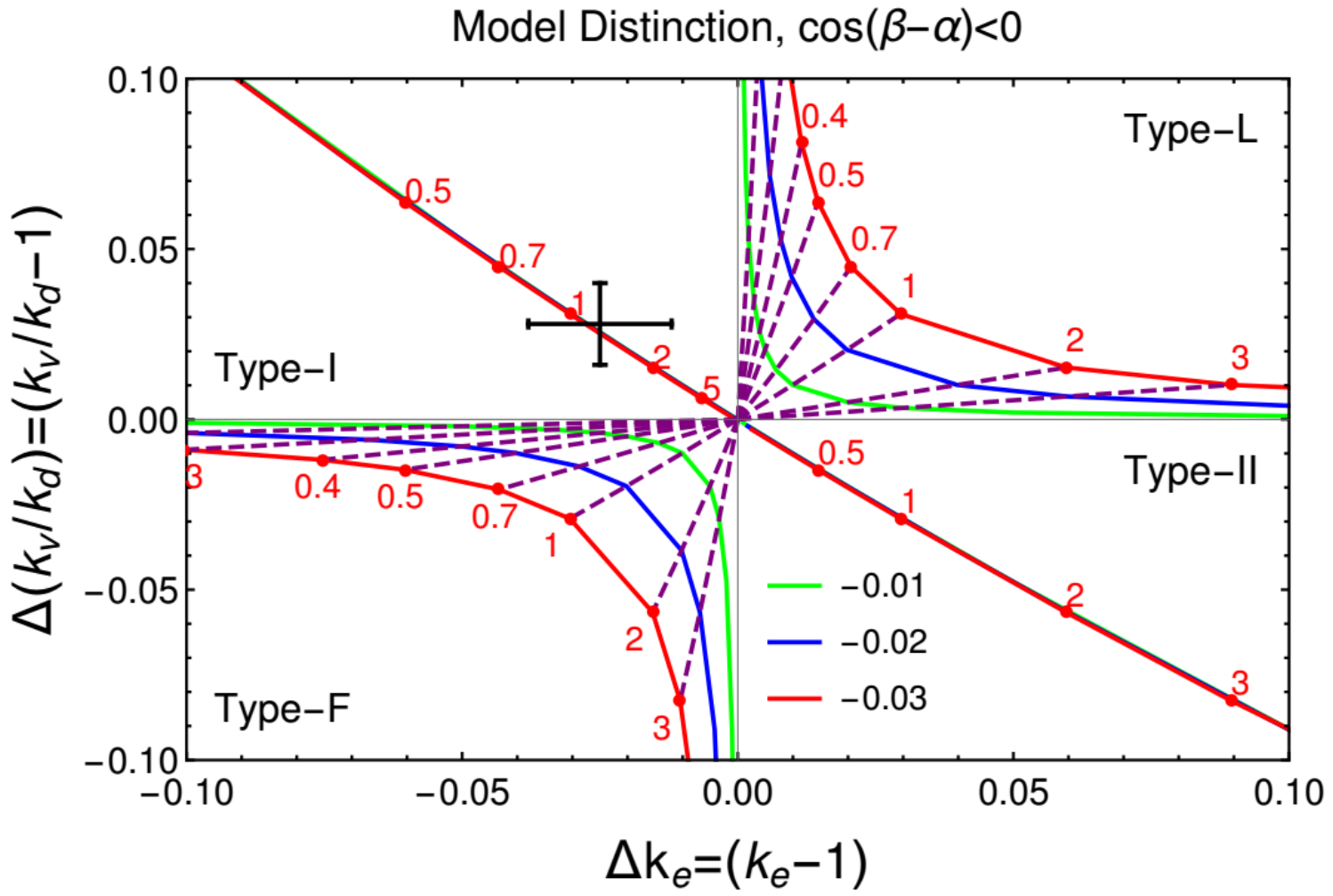
$\cos(\beta - \alpha)$

0.01

0.02

0.03

2HDM: Tree Level Model Distinction



Varying $\tan\beta$

$\cos(\beta-\alpha)$

0.01

0.02

0.03

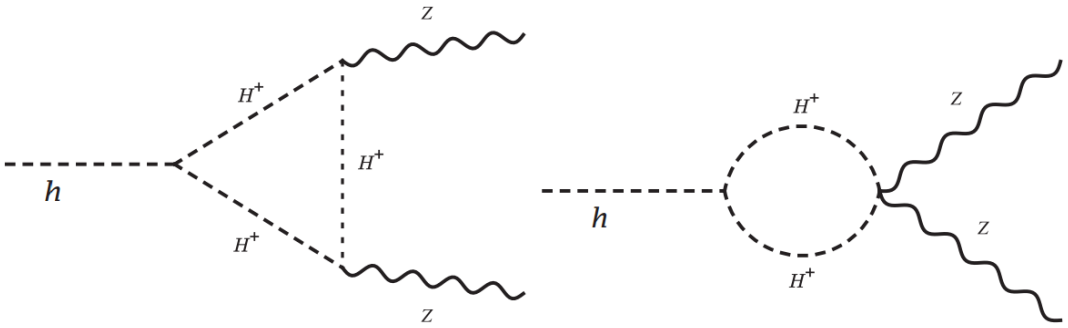
Type-I ↔ Type-II

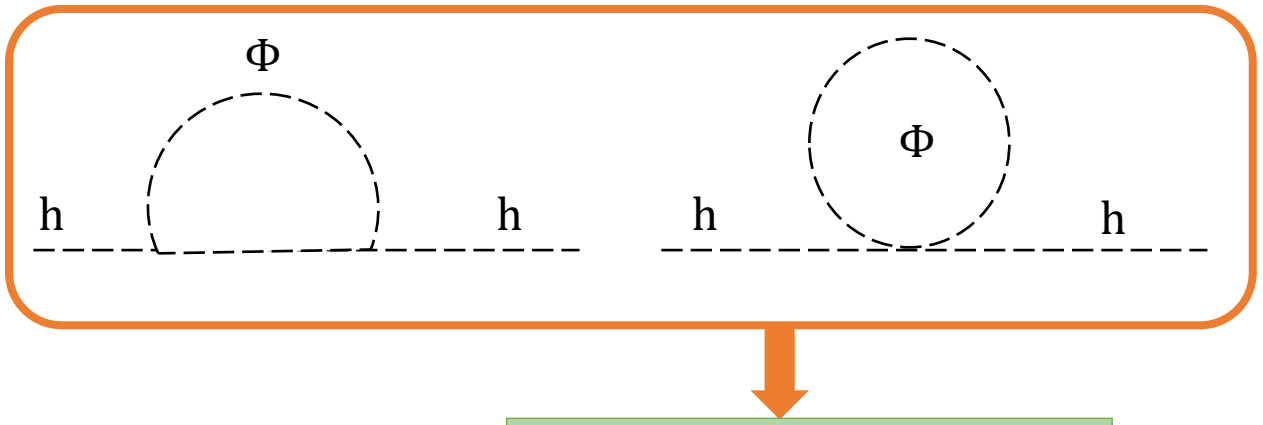
Type-L ↔ Type-F

Outline

- Higgs and Z-pole Precision Measurements
- Study strategies
- **Study Results:** Tree **& one-loop Level**
- 2HDM & Electroweak Phase Transition
- Summary

2HDM: One-Loop Level





Main contribution

Parameter : $\cos(\beta-\alpha), \tan\beta, m_H, m_A, m_{H^\pm}, m_{12}^2$

① Loop + degenerate: $\cos(\beta-\alpha)=0,\ m_\Phi \equiv m_H = m_A = m_{H^\pm}$

② Tree + Loop + degenerate: $\cos(\beta-\alpha)\neq 0\ ,\ m_\Phi \equiv m_H = m_A = m_{H^\pm}$

③ Tree + Loop + non-degenerate: $\Delta m_a = m_A - m_H,\ \Delta m_c = m_{H^\pm} - m_H$

2HDM: theoretical consideration

- Vacuum Stability

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2},$$

$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}.$$

- Unitary $|\lambda_i| \leq 4\pi$

- Perturbativity $|\Lambda_i \leq 16\pi|$

$$\Lambda_{1,2} = \lambda_3 \pm \lambda_4,$$
$$\Lambda_{3,4} = \lambda_3 \pm \lambda_5,$$
$$\Lambda_{5,6} = \lambda_3 + 2\lambda_4 \pm 3\lambda_5,$$
$$\Lambda_{7,8} = \frac{1}{2}\left[(\lambda_1 + \lambda_2) \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4\lambda_4^2}\right],$$
$$\Lambda_{9,10} = \frac{1}{2}\left[(\lambda_1 + \lambda_2) \pm \sqrt{(\lambda_1 - \lambda_2)^2 + 4|\lambda_5|^2}\right],$$
$$\Lambda_{11,12} = \frac{1}{2}\left[3(\lambda_1 + \lambda_2) \pm \sqrt{9(\lambda_1 - \lambda_2)^2 + 4(2\lambda_3 + \lambda_4)^2}\right]$$

2HDM: theoretical consideration

- Vacuum Stability

$$\lambda_1 > 0, \quad \lambda_2 > 0, \quad \lambda_3 > -\sqrt{\lambda_1 \lambda_2},$$

$$\lambda_3 + \lambda_4 - |\lambda_5| > -\sqrt{\lambda_1 \lambda_2}.$$

- Unitary $|\lambda_i| \leq 4\pi$

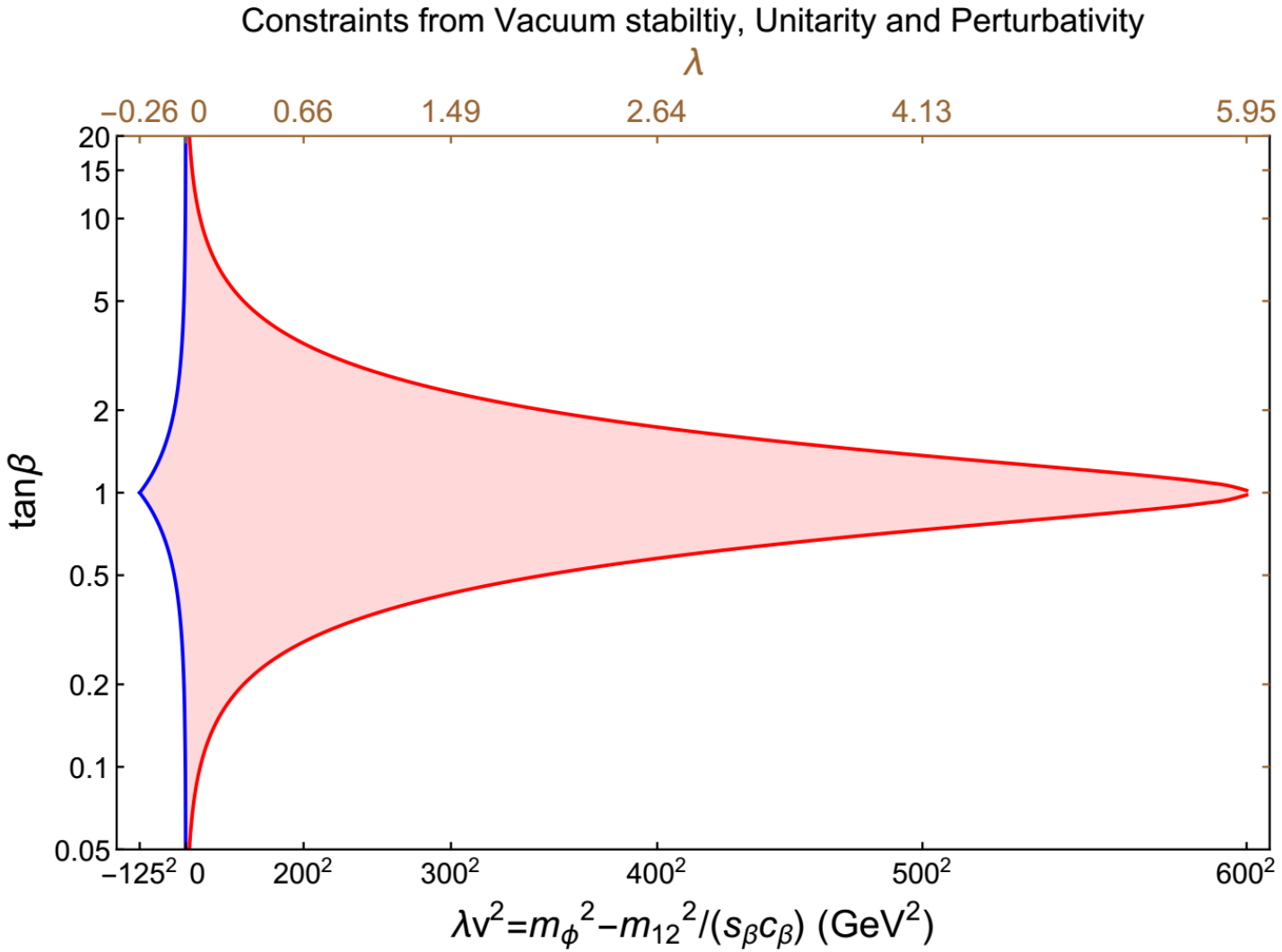
- Perturbativity $|\Lambda_i \leq 16\pi|$

$\cos(\beta - \alpha) = 0,$
$m_\Phi \equiv m_H = m_A = m_{H^\pm}$

$$\begin{aligned}
v^2\lambda_1 &= m_h^2 + t_\beta^2 \lambda v^2\,, \\
v^2\lambda_2 &= m_h^2 + \lambda v^2/t_\beta^2\,, \\
v^2\lambda_3 &= m_h^2 + \lambda v^2\,, \\
v^2\lambda_4 &= -\lambda v^2\,, \\
v^2\lambda_5 &= -\lambda v^2\,.
\end{aligned}$$

2 Free parameters

2HDM: theoretical consideration



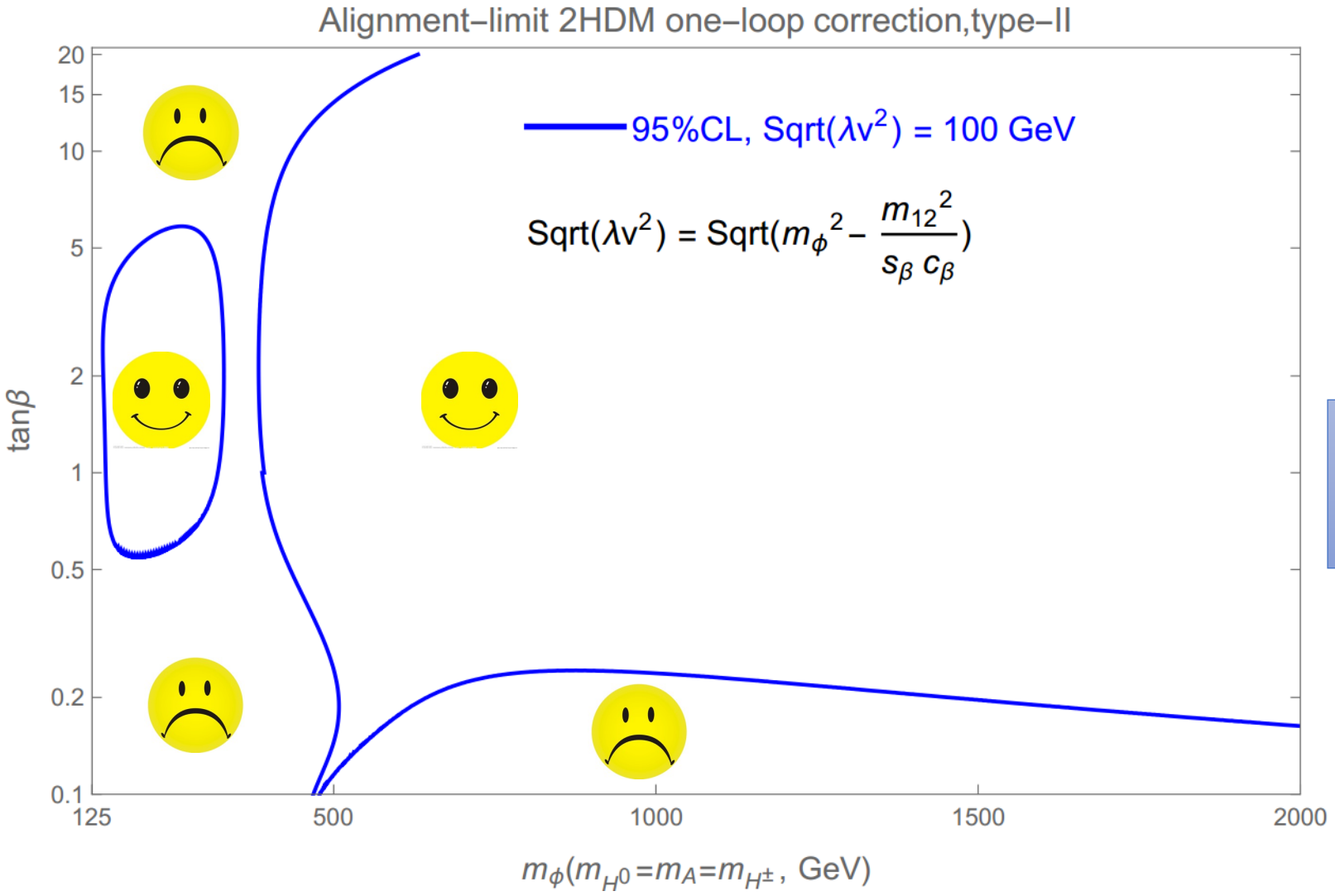
$$\cos(\beta-\alpha)=0,$$
$$m_\Phi \equiv m_H = m_A = m_{H^\pm}$$

Theoretical constraints

$$-125^2\mathrm{GeV}^2 < \lambda v^2 < 600^2\mathrm{GeV}^2$$

$$\lambda \in (-0.26, 5.95)$$
$$\lambda_4 = \lambda_5 = \lambda_3 - 0.258 = -\lambda$$

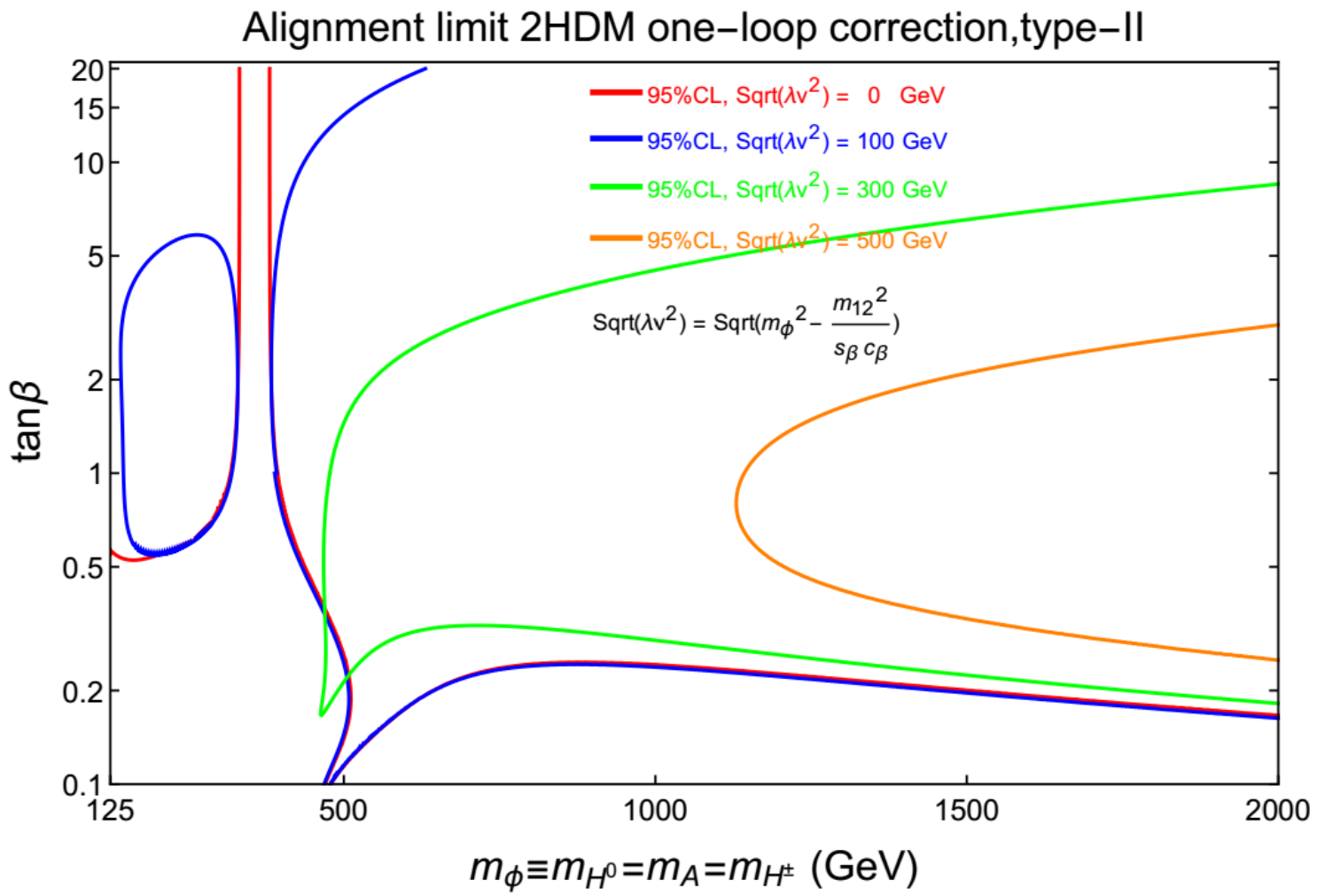
2HDM: *Loop + degenerate*



CEPC fit,
Type-II

$\cos(\beta-\alpha)=0,$
$m_\Phi \equiv m_H = m_A = m_{H^\pm}$

2HDM: *Loop + degenerate*



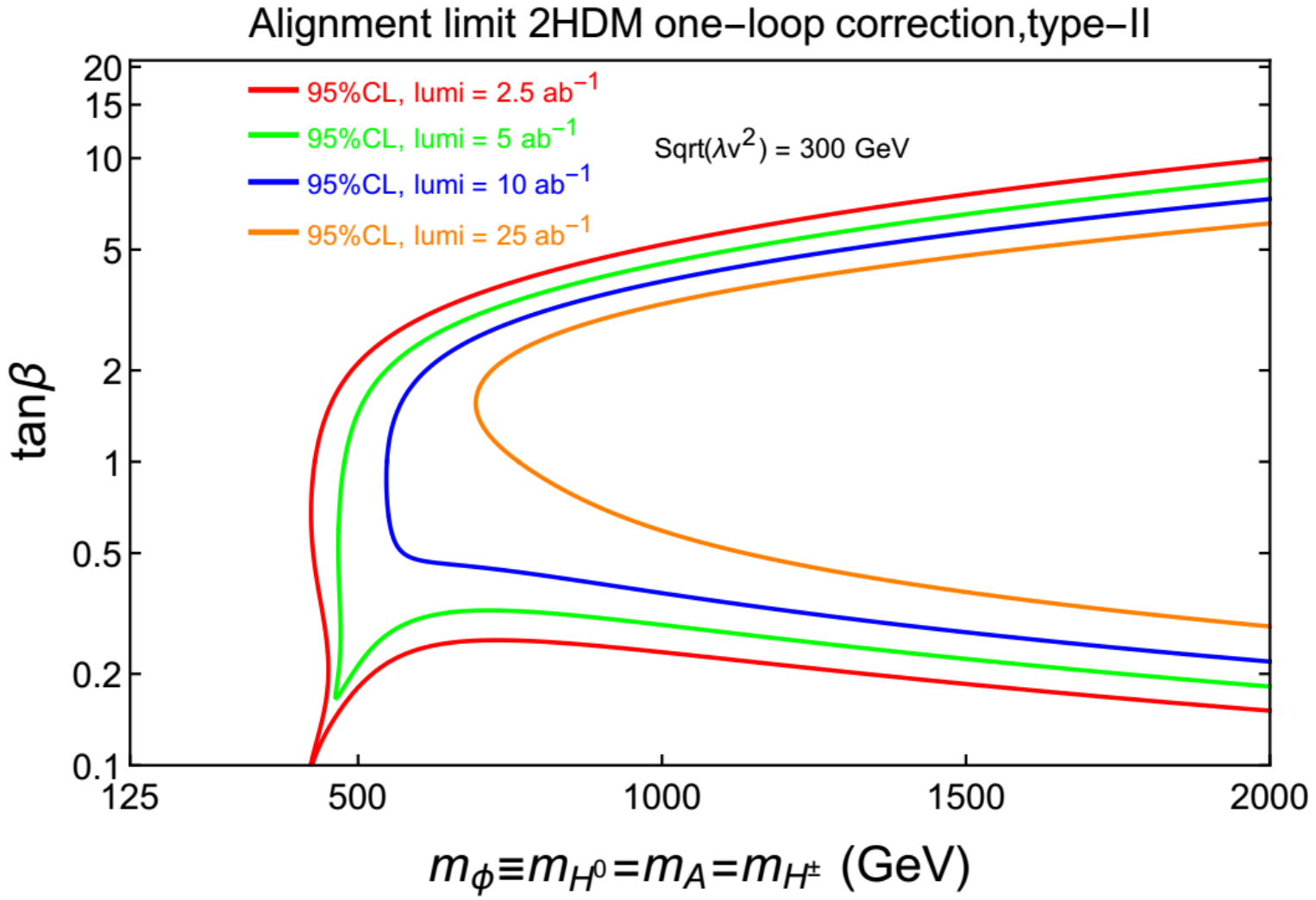
CEPC fit, Type-II

$-125^2\mathrm{GeV}^2 < \lambda v^2 < 600^2\mathrm{GeV}^2$

Sqrt(λv^2)	$m_\Phi >$
100	400
300	500
500	1100

(GeV)

2HDM: *Loop + degenerate*



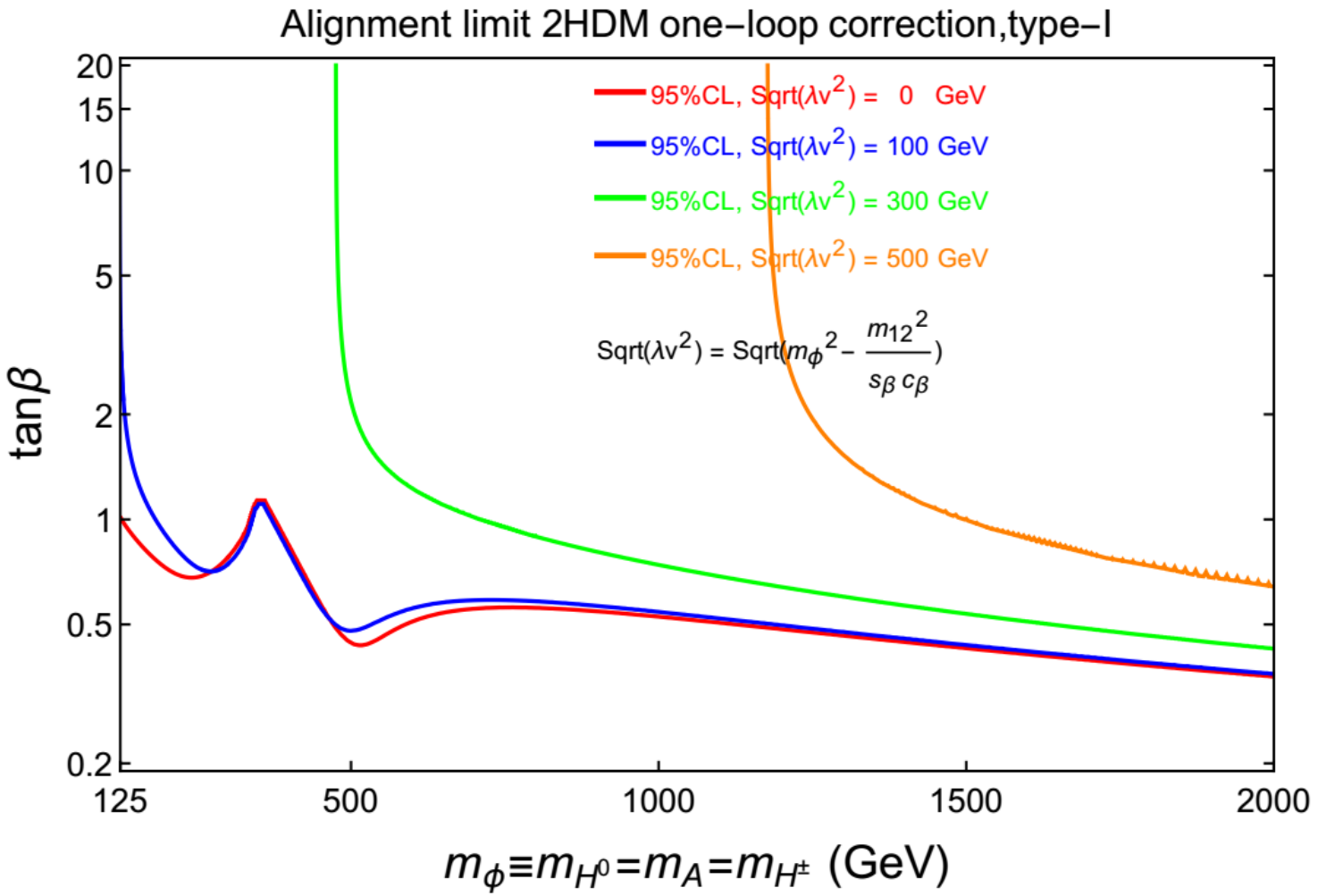
CEPC fit, Type-II

$\lambda v^2 = 300^2 \mathrm{GeV}^2$

Lumi = 25 ab^{-1}

$m_\Phi > 700$ GeV

2HDM: *Loop + degenerate*



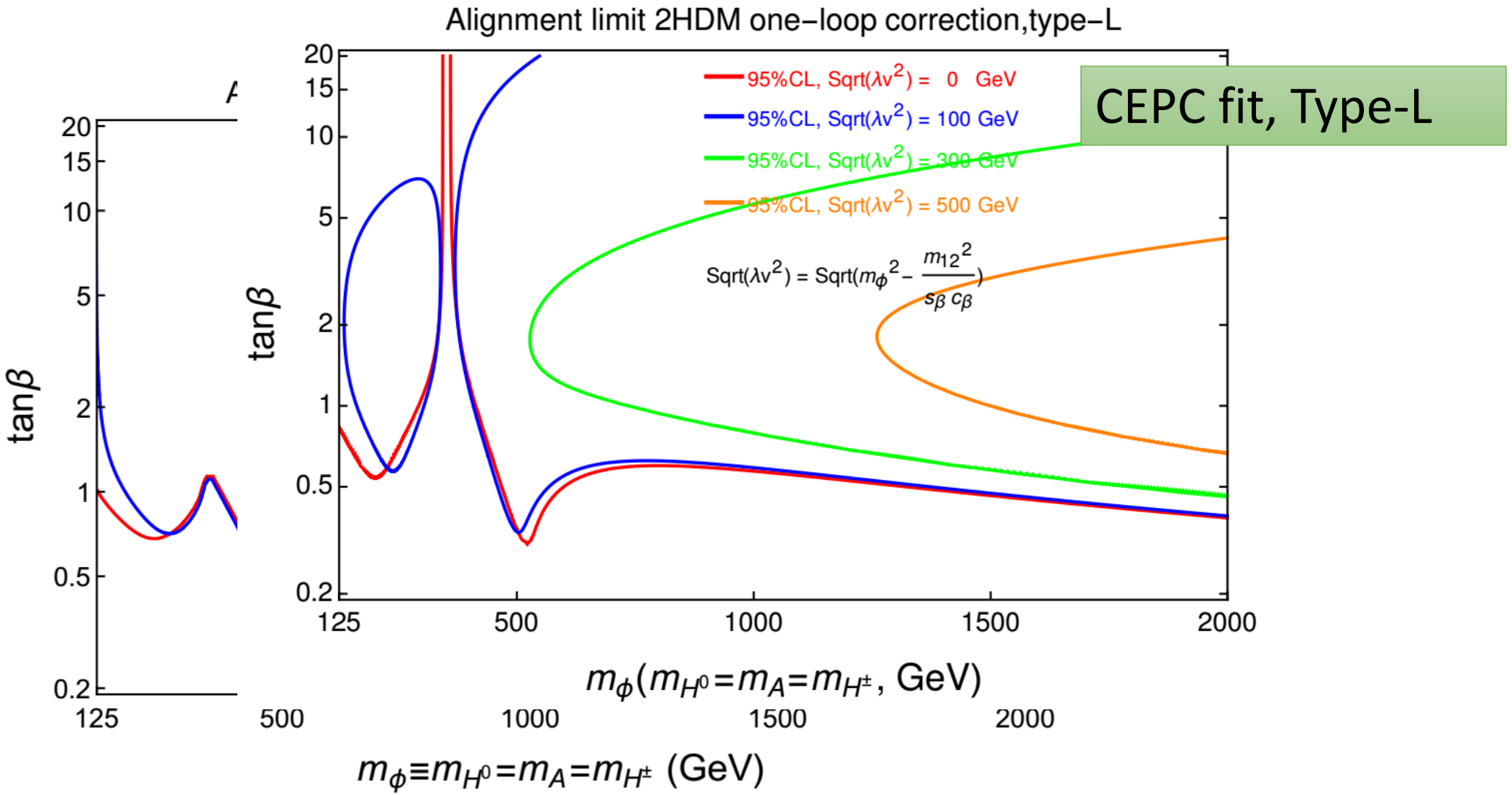
CEPC fit, Type-I

$-125^2\mathrm{GeV}^2 < \lambda v^2 < 600^2\mathrm{GeV}^2$

Sqrt(λv^2)	$m_\Phi >$
100	--
300	500
500	1100

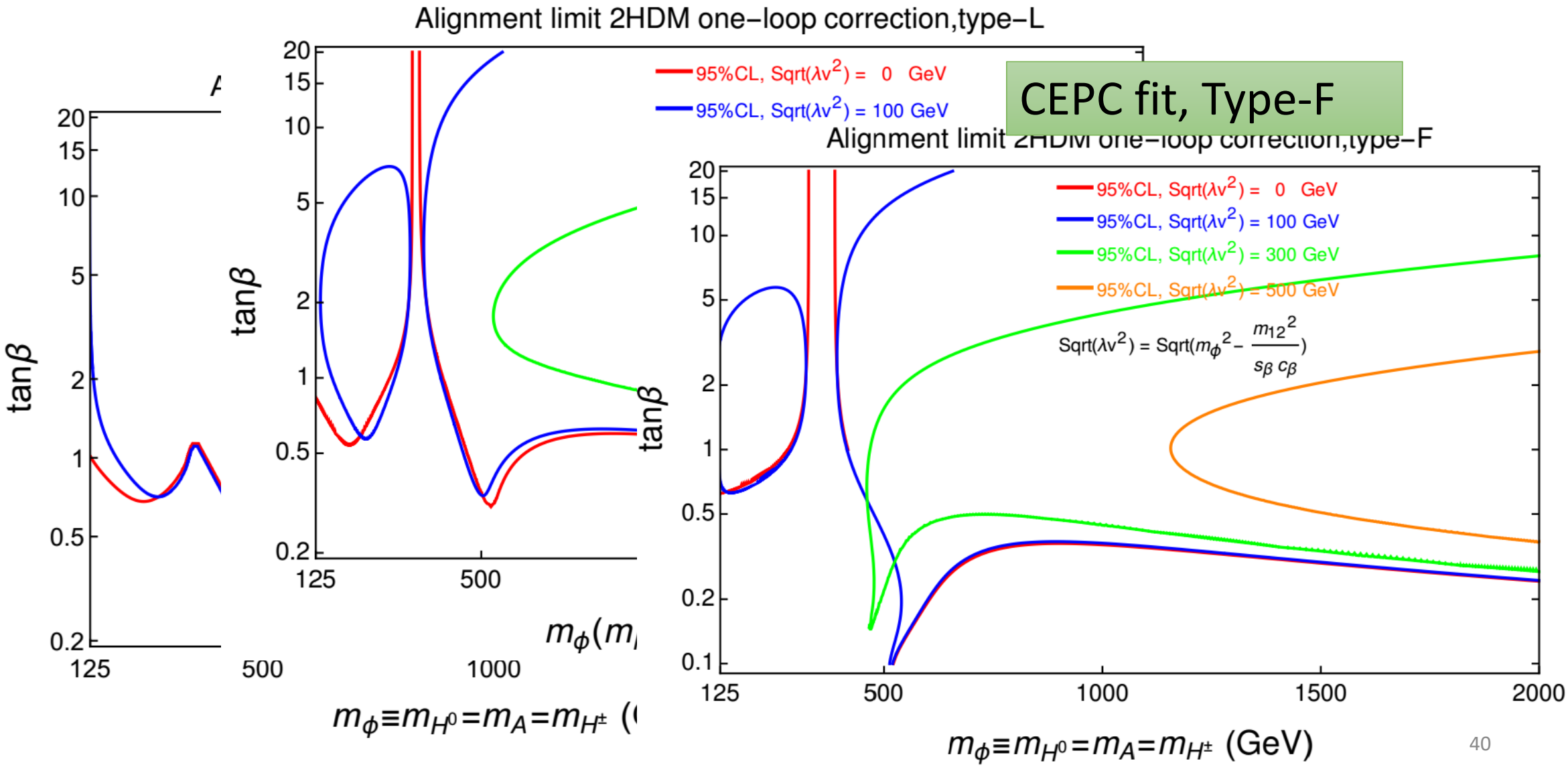
(GeV)

2HDM: *Loop + degenerate*



CEPC fit, Type-L

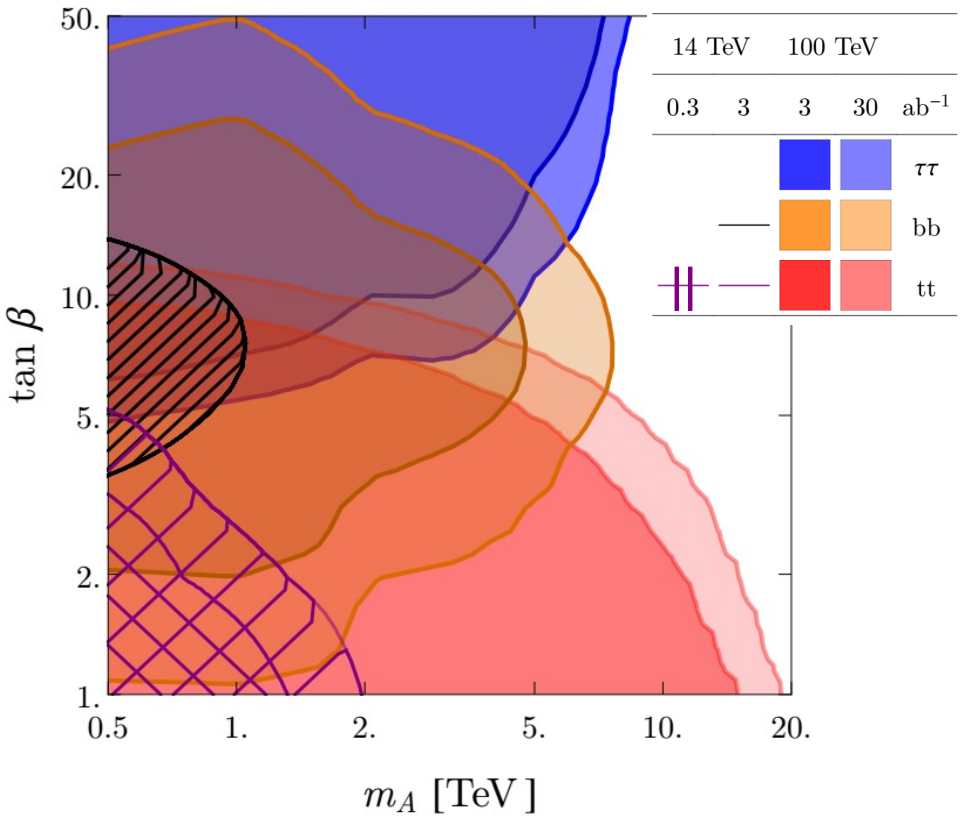
2HDM: *Loop + degenerate*



Higgs direct search at LHC

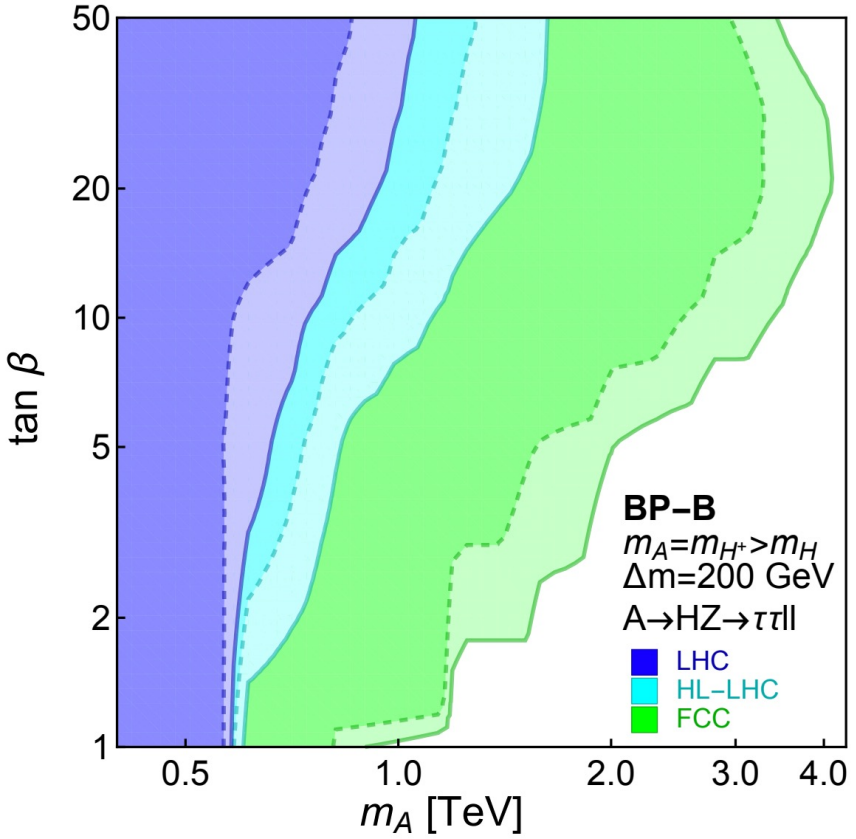
Type-II

Conventional Search



Craig et. al., 1605.08744

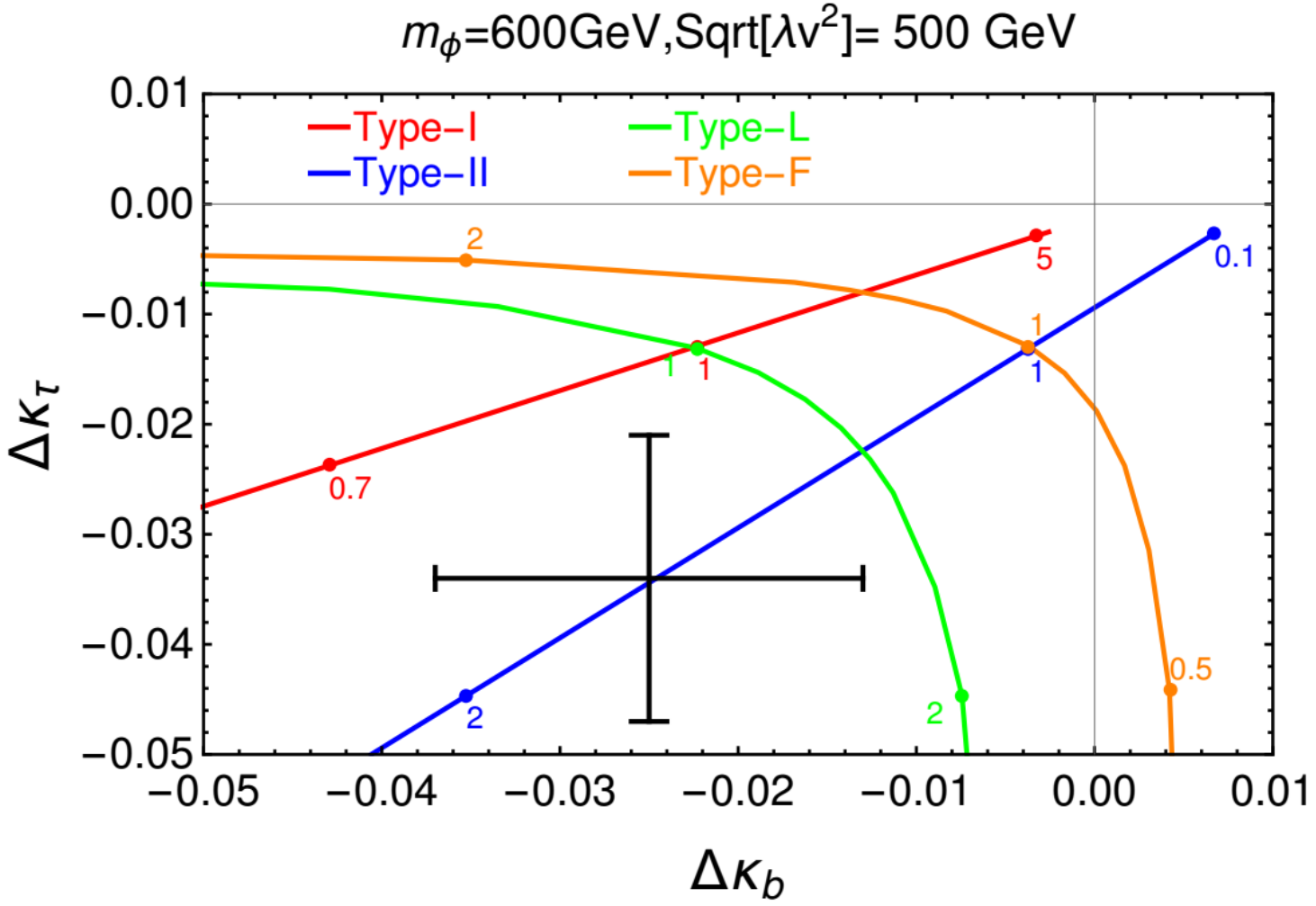
Exotic: A -> HZ



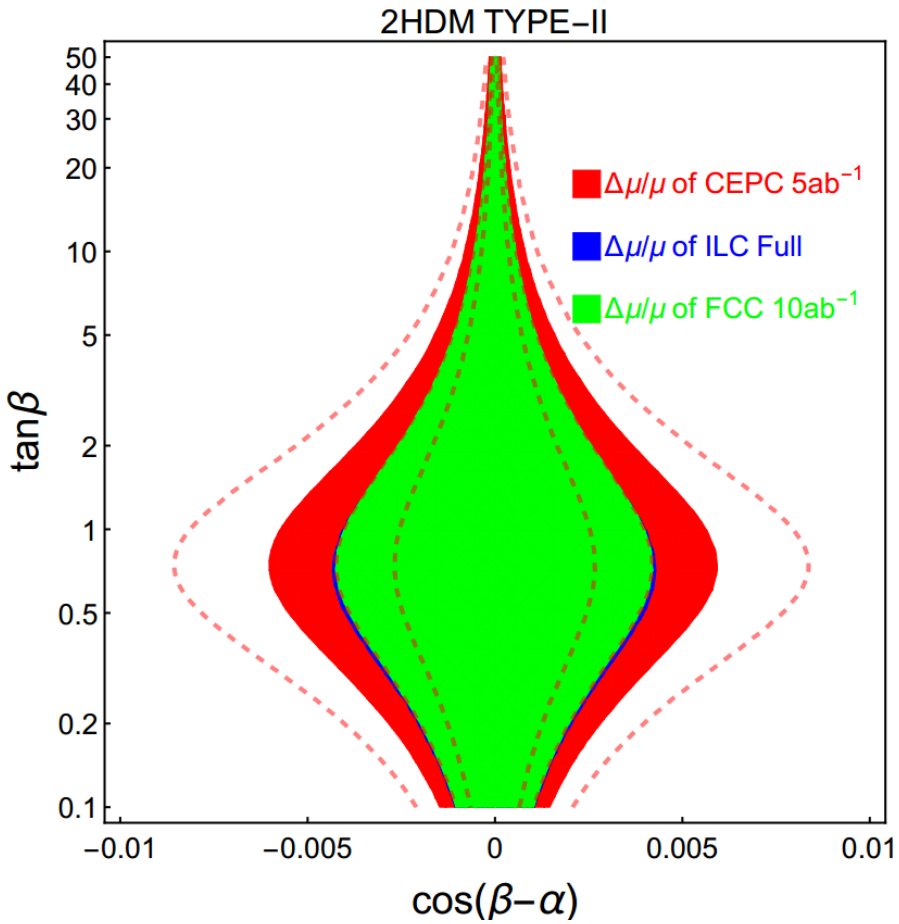
S. Su et. al., 1812.01633

2HDM: *Loop + degenerate*

Varying $\tan\beta$



2HDM: *Tree + Loop + degenerate*

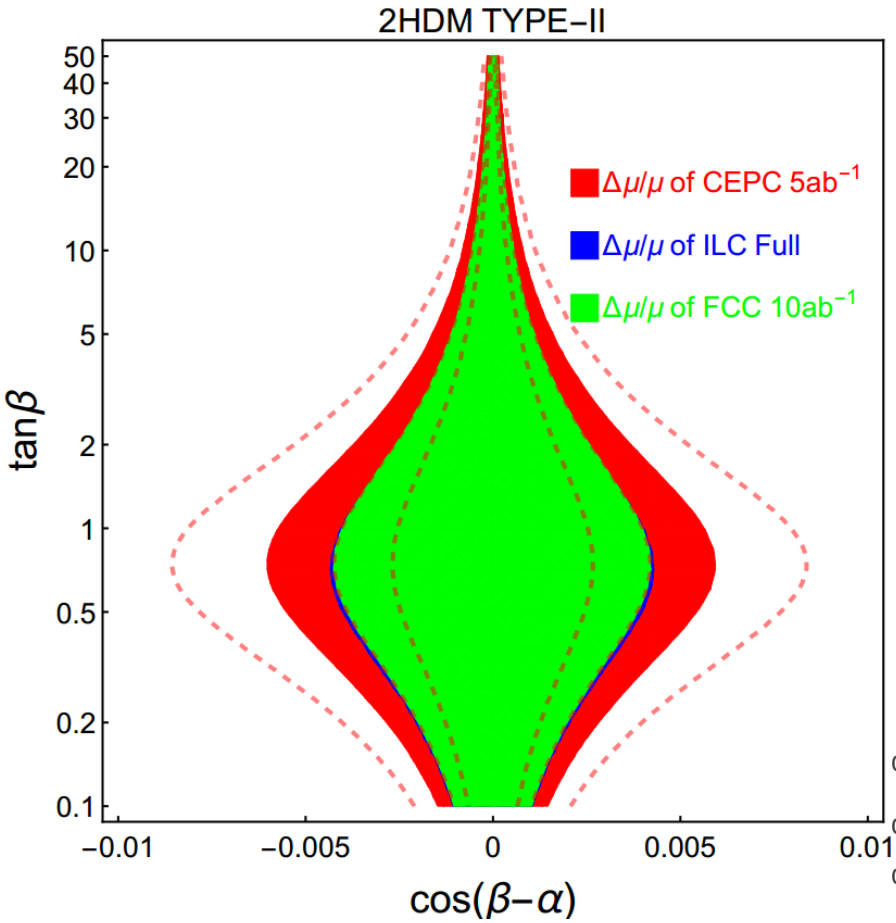


$\cos(\beta - \alpha) \neq 0,$

$m_\Phi \equiv m_H = m_A = m_{H^\pm}$

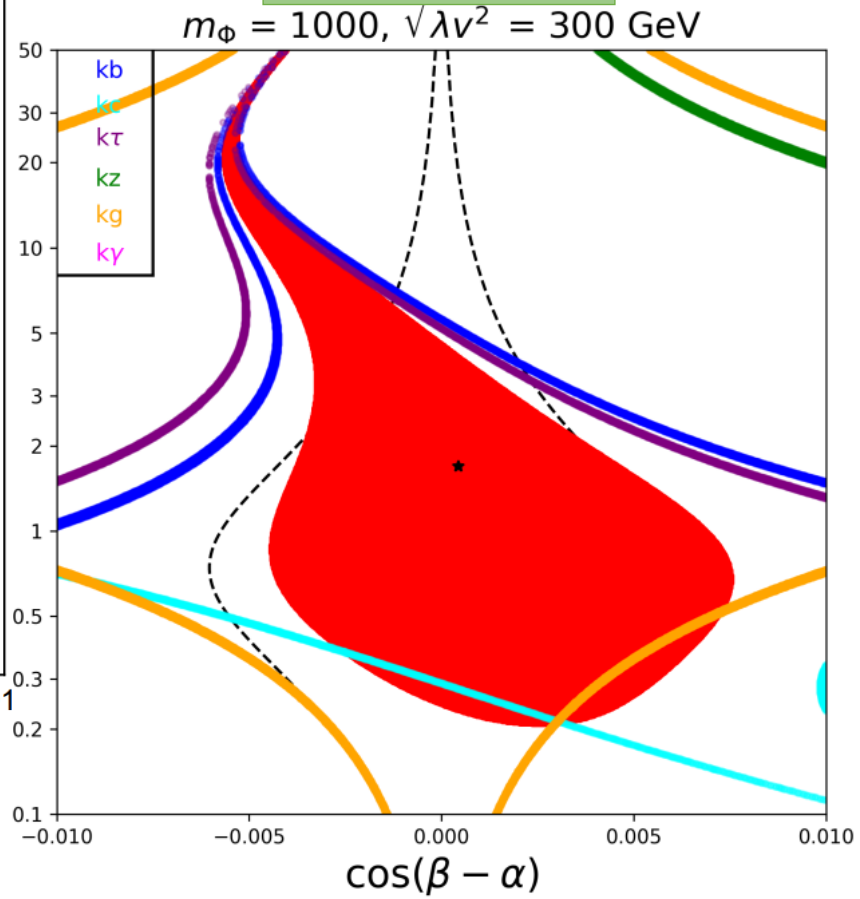
Tree-level

2HDM: *Tree + Loop + degenerate*

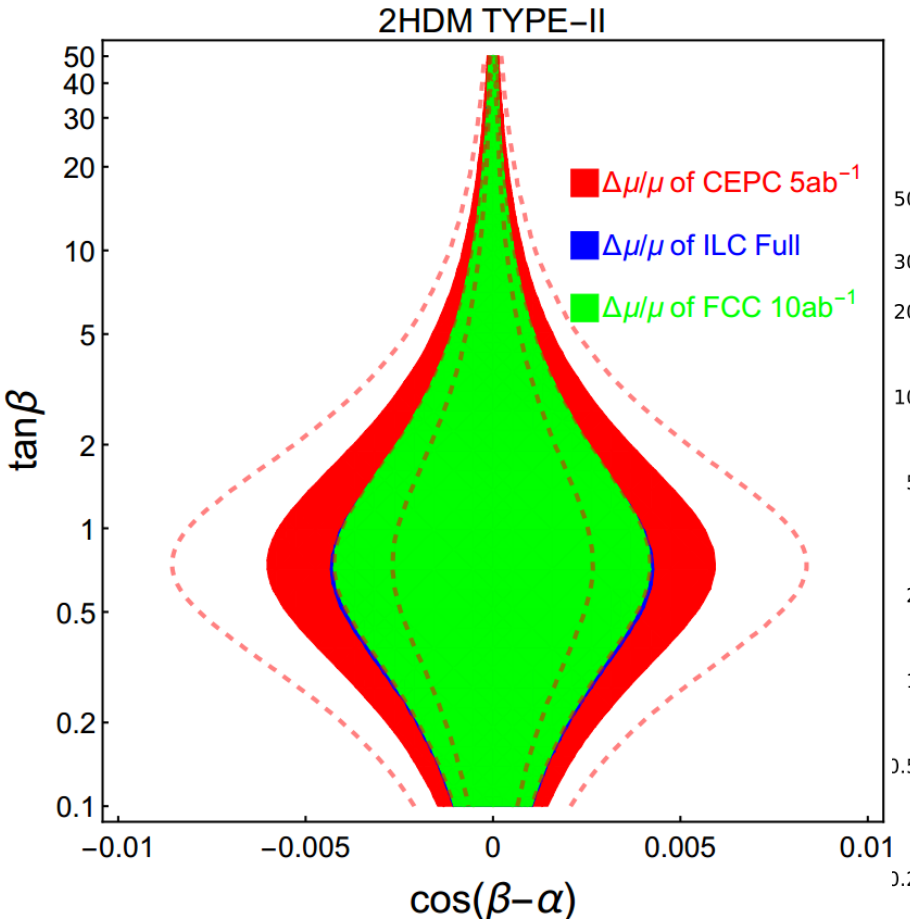


Tree-level

Loop-level

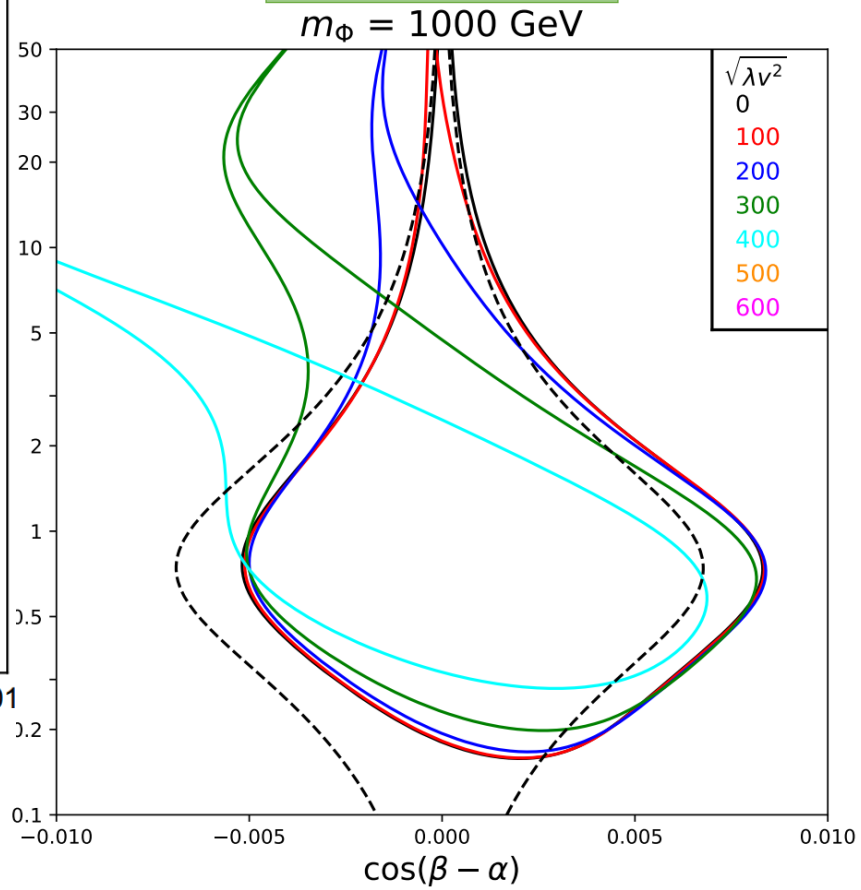


2HDM: *Tree + Loop + degenerate*

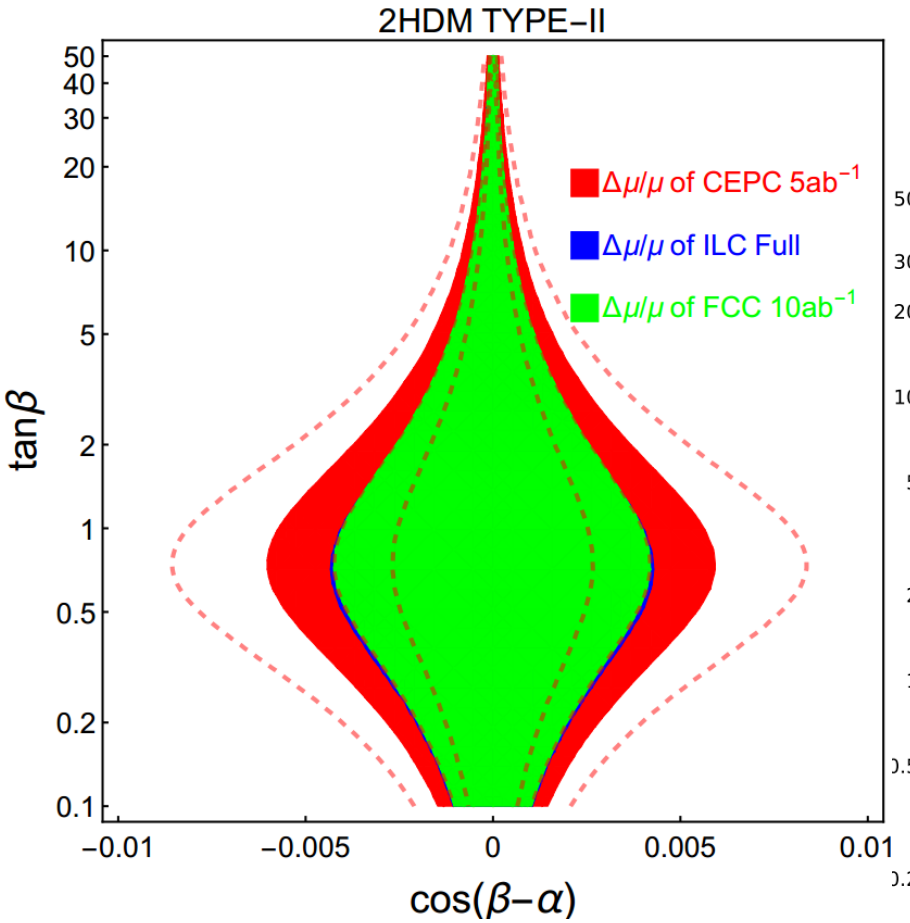


Tree-level

Loop-level

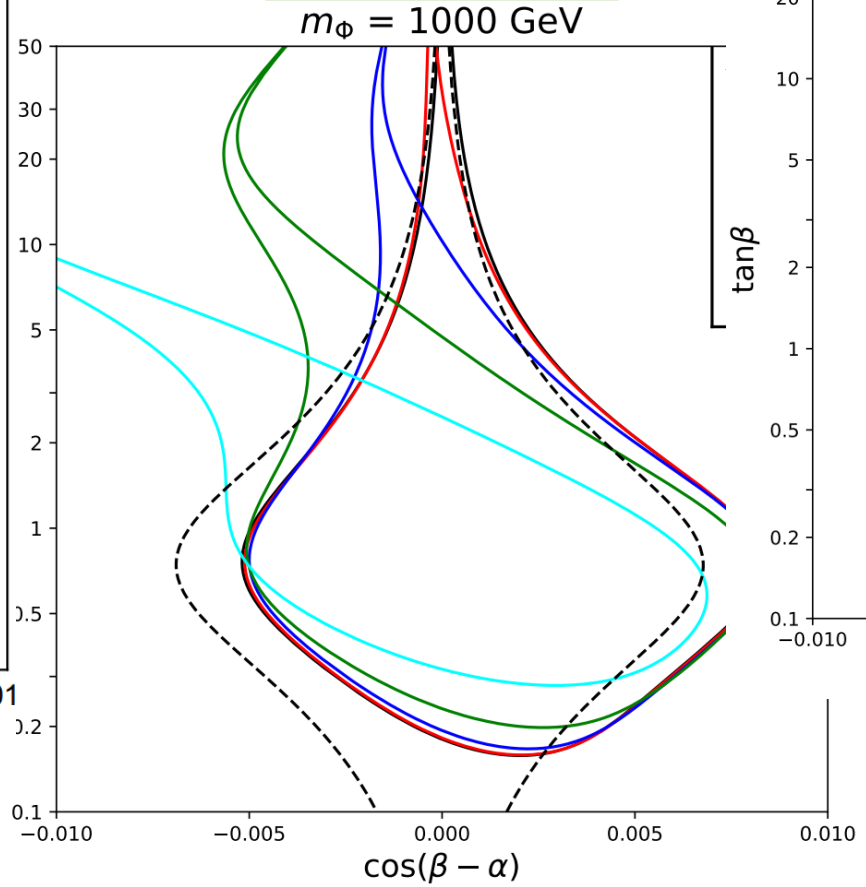


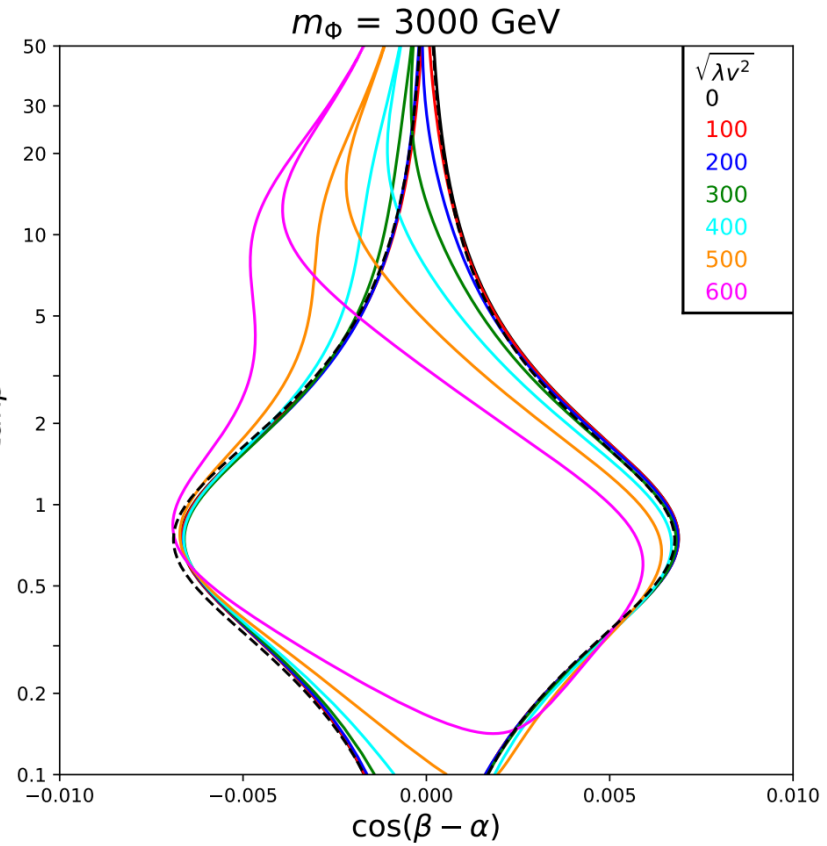
2HDM: *Tree + Loop + degenerate*



Tree-level

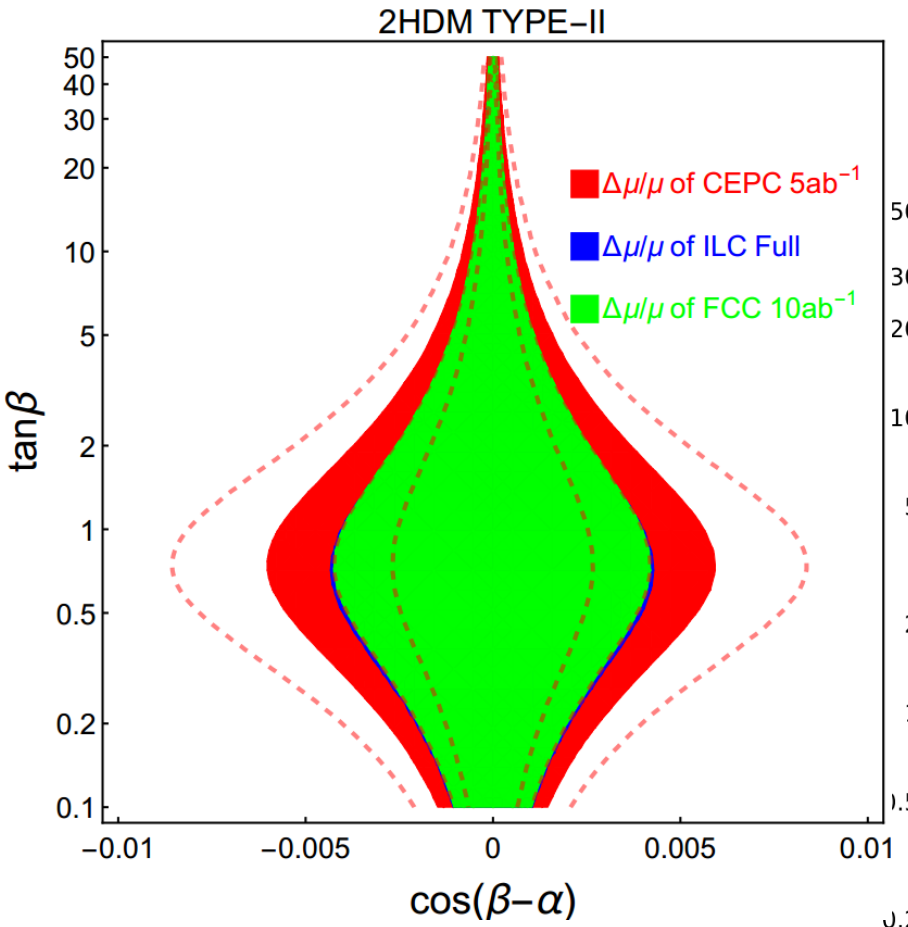
Loop-level





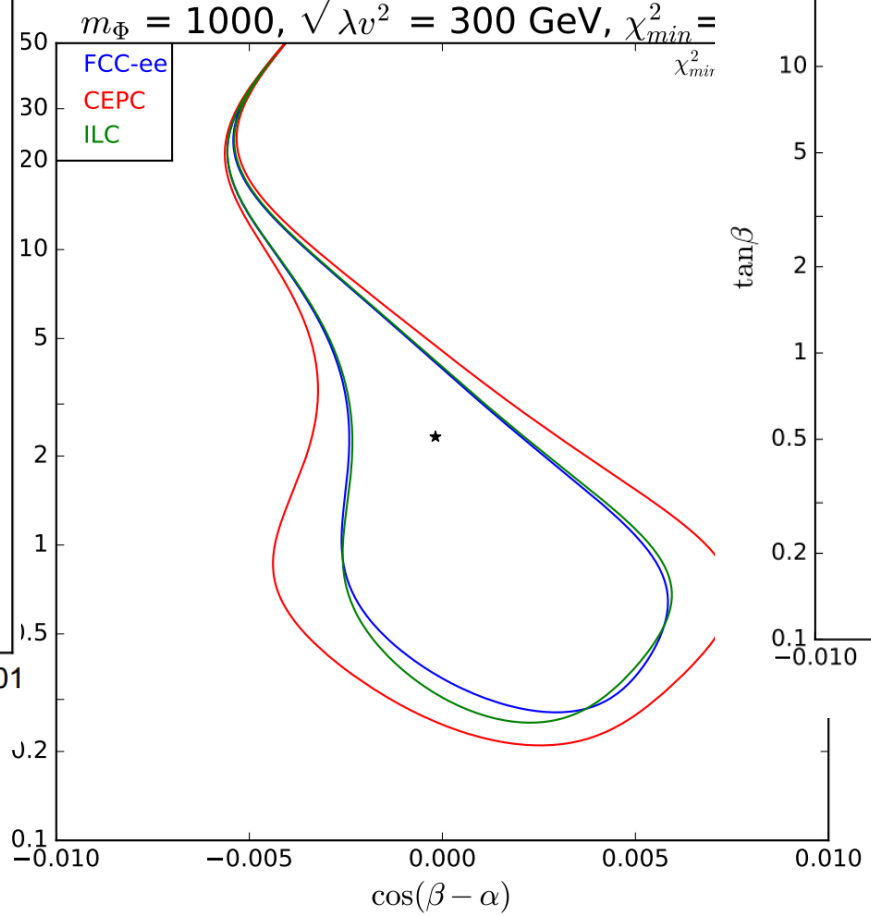
Loop-level decouple

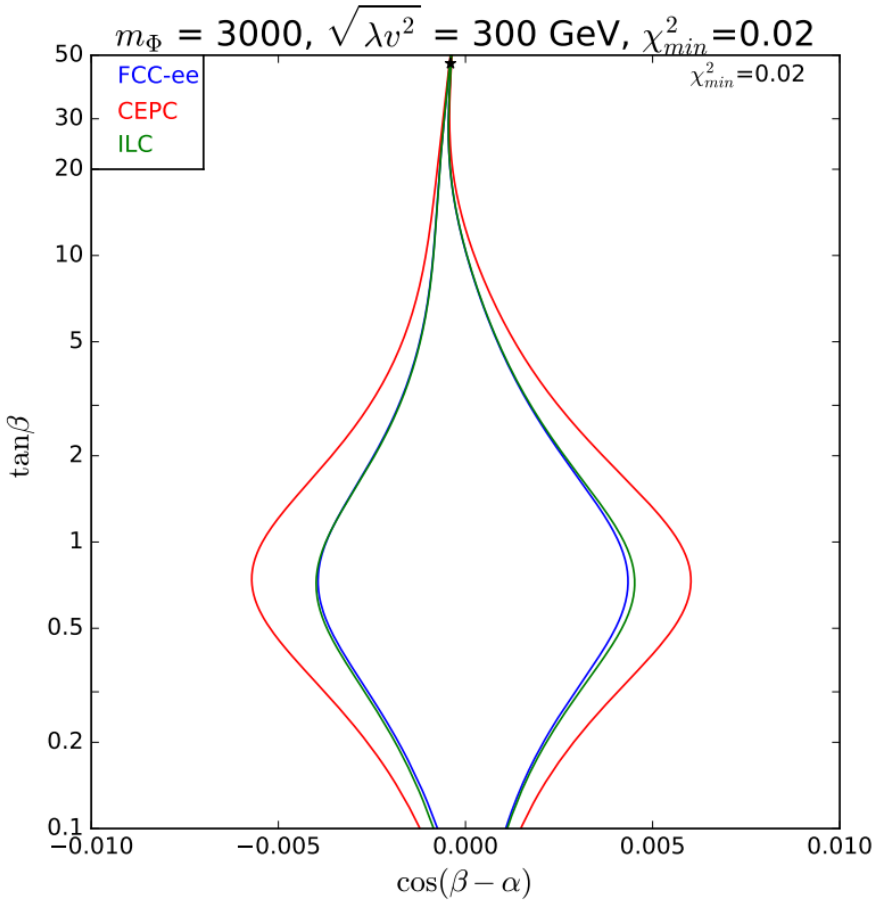
2HDM: *Tree + Loop + degenerate*



Tree-level

Loop-level





2HDM: $Tree + Loop + non - degenerate$

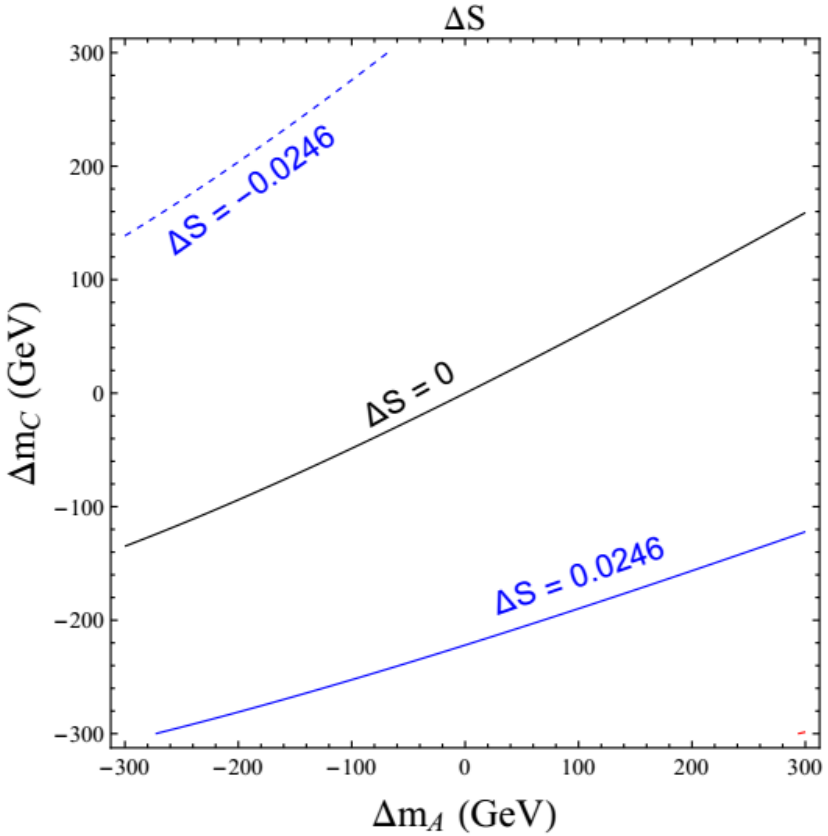
Z Pole Precision

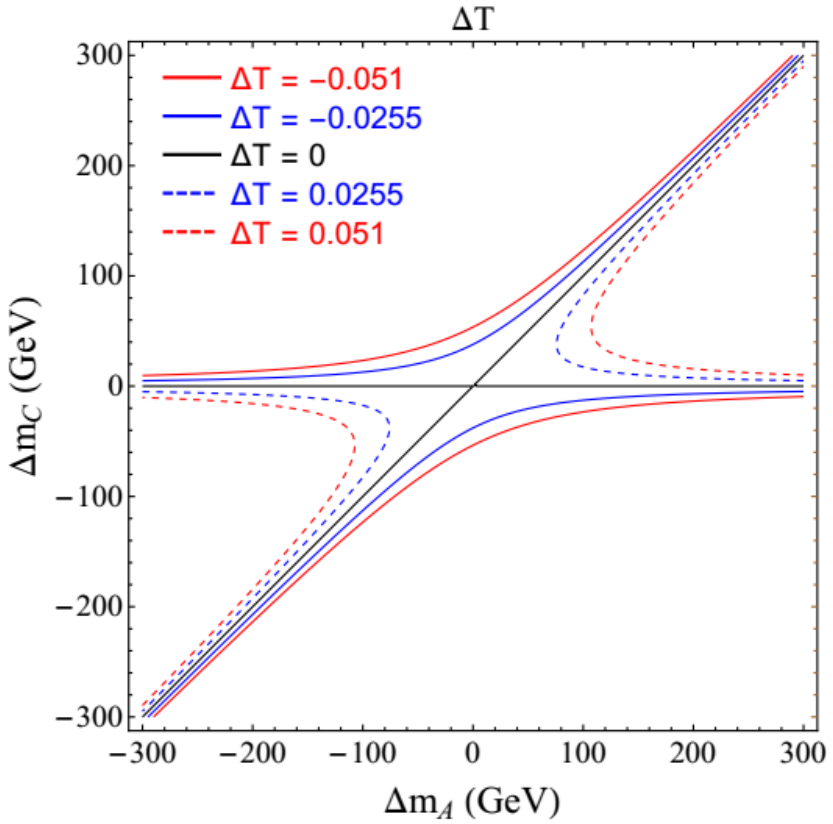
	Current (1.7×10^7 Z's)				CEPC ($10^{10} Z$'s)				FCC-ee ($7 \times 10^{11} Z$'s)				ILC ($10^9 Z$'s)			
	σ	correlation			σ	correlation			σ	correlation			σ	correlation		
		S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U	(10^{-2})	S	T	U
S	0.04 ± 0.11	1	0.92	−0.68	2.46	1	0.862	−0.373	0.67	1	0.812	0.001	3.53	1	0.988	−0.879
T	0.09 ± 0.14	–	1	−0.87	2.55	–	1	−0.735	0.53	–	1	−0.097	4.89	–	1	−0.909
U	-0.02 ± 0.11	–	–	1	2.08	–	–	1	2.40	–	–	1	3.76	–	–	1

2HDM: $Tree + Loop + non-degenerate$

Z Pole Precision

	Current
	σ
S	0.04 ± 0.11
T	0.09 ± 0.14
U	-0.02 ± 0.1





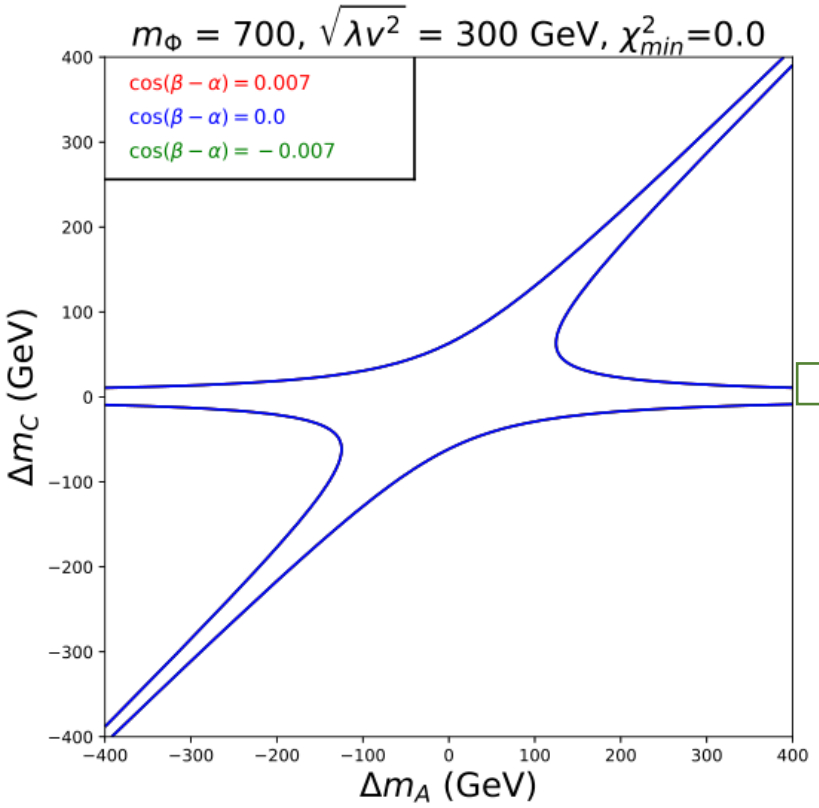
$(10^9 Z$'s)	
correlation	
T	U
0.988	−0.879
1	−0.909
–	1

2HDM: $Tree + Loop + non - degenerate$

CEPC fit

$$\Delta m_A = m_A - m_H,$$
$$\Delta m_C = m_{H^\pm} - m_H,$$
$$m_H = 700\ \text{GeV}$$

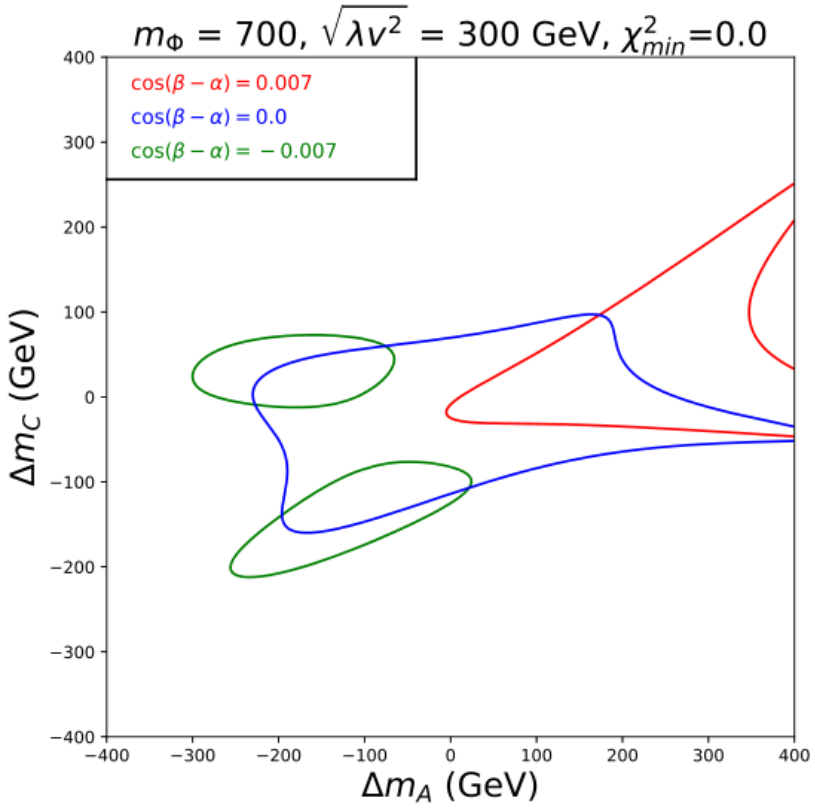
Z Pole Precision



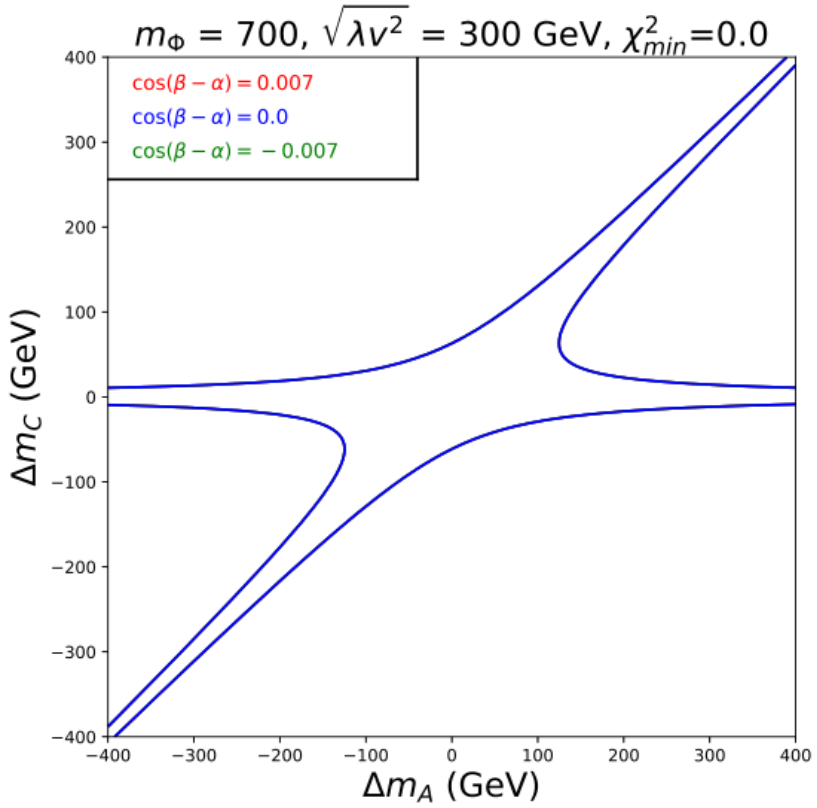
$$m_{H^\pm} = m_H$$
$$m_{H^\pm} = m_A$$

2HDM: $Tree + Loop + non - degenerate$

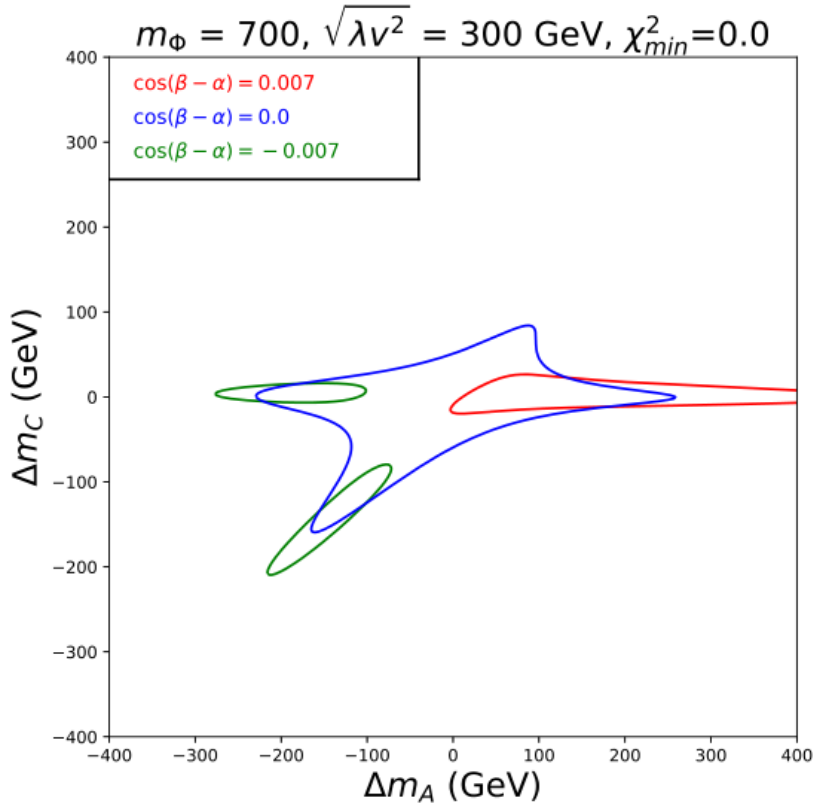
Higgs Precision



Z Pole Precision



Combined

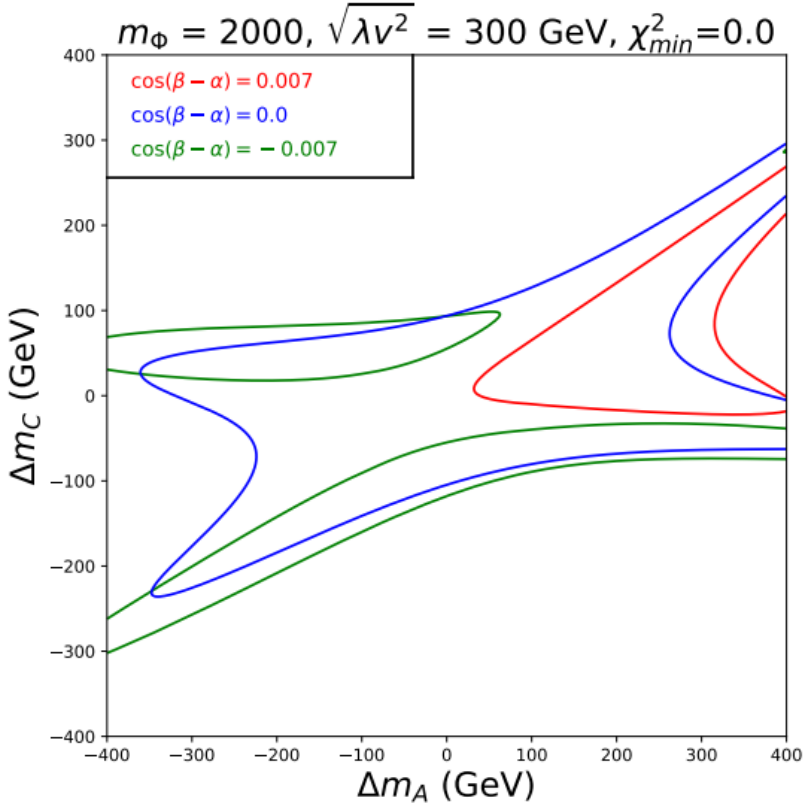


$m_H = 700$ GeV

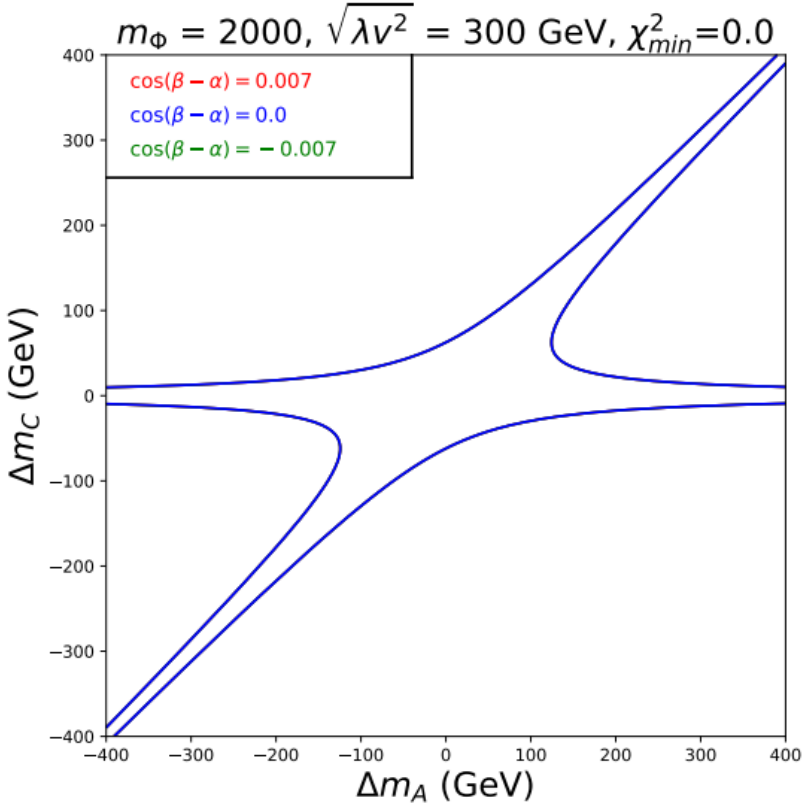
Complementary to each other

2HDM: $Tree + Loop + non - degenerate$

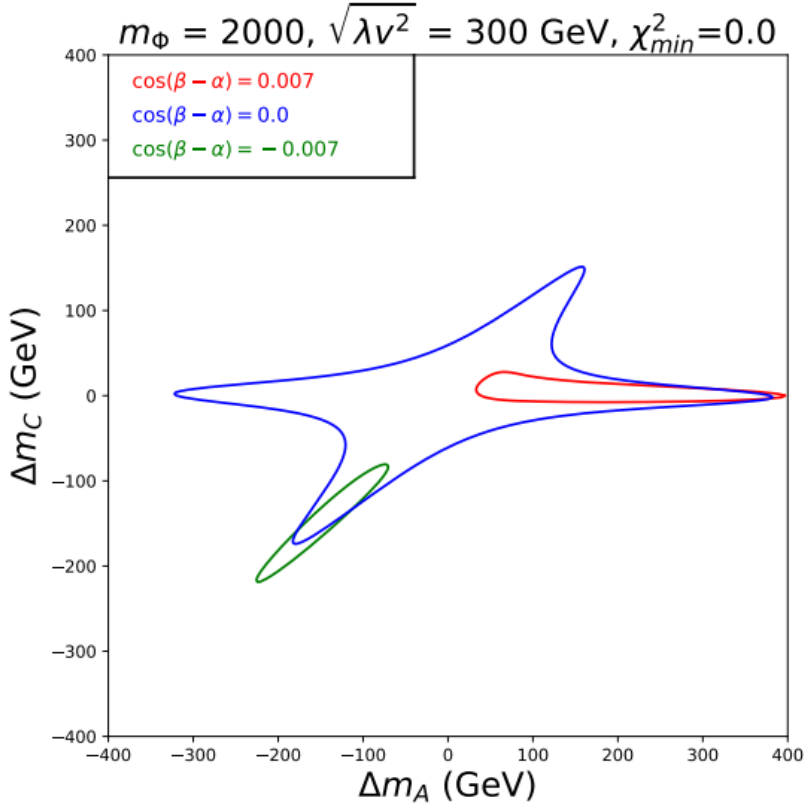
Higgs Precision



Z Pole Precision



Combined

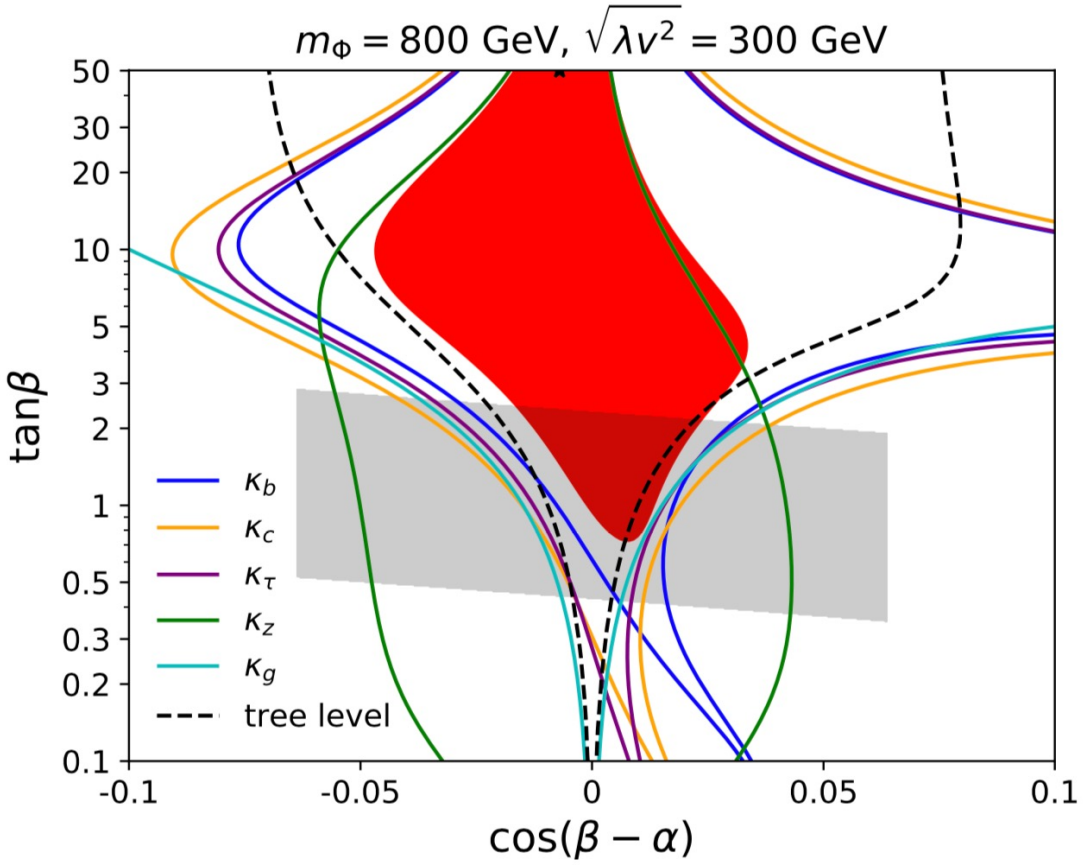


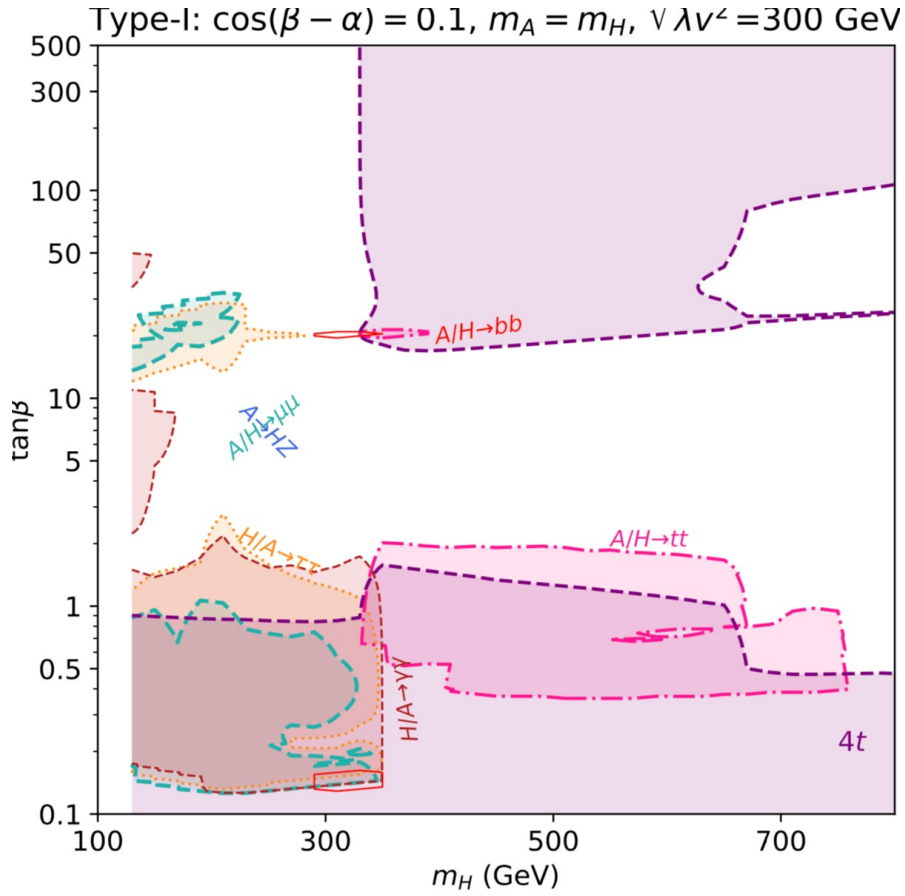
$m_H = 2000$ GeV

Complementary to each other

2HDM: Type-I

Constraints at Large tanβ





1912.01431 N. Chen, T. Han, S. Su, Y. Wu

Summary 1: Higgs precision

2HDM

- Tree vs Loop
- Alignment vs Non-alignment
- Degenerate vs Non-gedenerate

Complementary to

- Z pole precision
- LHC direct search